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SYNOPTICAL AND TOPICAL

INDEX

OF

A. I. E. E. TRANSACTIONS

Vol. XXX, Parts I, II and III

Prepared under the supervision of the Committee on Indexing the Transactions

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The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

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1. EDUCATION

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Ralph D. Mershon **Vol. xxx—1911, pp. 2337-2344**

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Charles P. Steinmetz **Vol. xxx—1911, pp. 367-385**

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W. S. Franklin **Vol. xxx—1911, pp. 581-585**

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COMMERCIAL PROBLEMS OF TRANSFORMER DESIGN

H. R. Wilson **Vol. xxx—1911, pp. 219-223**

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THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL

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Harris J. Ryan **Vol. xxx—1911, pp. 1-76**

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Description of similar investigations by the Bureau of Standards and others. Criticism of the authors' methods, especially of the high e.m.fs. used. Account of actual example of corrosion in a building.

6. MAGNETIC PROPERTIES AND TESTING OF IRON

HYSTERESIS AND EDDY-CURRENT EXPONENTS FOR SILICON STEEL

W. J. Wooldridge **Vol. xxx—1911, pp. 215-217**

Results of tests plotted in the form of curves.

Discussion, incorporated with that of paper by H. R. Wilson on " Commercial Problems of Transformer Design."

COMMERCIAL TESTING OF SHEET IRON FOR HYSTERESIS LOSS

L. T. Robinson **Vol. xxx 1911 pp. 741-760**

Outline of the requirements of a shop method of testing iron. Description of testing outfits developed by the author, with results of tests of commercial iron. Relative accuracy and cost of testing compared with Epstein method.

Discussion, incorporated with that of paper by Malcolm MacLaren on " The Effect of Temperature upon the Hysteresis Loss in Sheet Steel."

THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL

Malcolm MacLaren **Vol. xxx—1911, pp. 761-775**

Description of iron loss tests on samples of iron at temperatures up to non-magnetic point. Eddy current and hysteresis coefficients and value of hysteresis loss plotted with temperature for different densities. Also a description of method of measuring hysteresis loss directly.

Discussion, (including that of paper by L. T. Robinson on " Commercial Testing of Sheet Iron for Hysteresis Loss ") pp. 776-802, by Messrs. C. H. Sharp, Edwin F. Northrup, J. A. Capp, L. W. Chubb, R. B. Treat, W. J. Wooldridge, W. R. Whitney, C. J. Fechheimer, C. A. Adams, W. S. Franklin, Malcolm MacLaren, L. T. Robinson, Henry Pikler, M. G. Lloyd and J. D. Ball.

General remarks on commercial methods of testing magnetic properties of iron. Relation between flux density and hysteresis exponent. Method of calculating the hysteresis exponent from observed iron losses.

MAGNETIC PROPERTIES OF IRON AT FREQUENCIES UP TO 200,000 CYCLES

E. F. W. Alexanderson **Vol. xxx—1911, pp 2433-2448**

Measurements of magnetizing core loss and skin effect at high frequencies. Methods of measuring power at high frequency. Relation between the various factors and frequency plotted as curves.

Discussion, pp. 2449-2454, by Messrs. Harold Pender, A. B. Behrend Charles P. Steinmetz, Reginald A. Fessenden, F. B. Silsbee.

Behavior of iron at high frequency.

8. TRANSFORMERS

OPEN ATMOSPHERE AND DRY TRANSFORMER OIL AS HIGH-VOLTAGE INSULATORS

Harris J. Ryan **Vol. xxx—1911, pp. 1-76**

Analytical study of corona formation and the factors which influence it, covering practically all the work that has thus far been done by the author and other investigators. Complete references to all original work. Brief explanation of the ionization theory, which is applied to explain the phenomena that take place on high tension lines. Laws formulated for calculation of critical e.m.f. under all conditions.

Discussion, incorporated with that of paper by E. L. West on " High Voltage Line Loss Tests made on the 100-Kilovolt, 60-Cycle, 180-Mile Transmission Line of the Central Colorado Power Company."

COMMERCIAL PROBLEMS OF TRANSFORMER DESIGN

H. R. Wilson **Vol. xxx—1911, pp. 219-223**

Brief mention of some of the commercial factors which enter into the design of transformers.

Discussion, (including that of paper by A. B. Hendricks, Jr., on " High Tension Testing of Insulating Materials " and W. J. Wooldridge on " Hysteresis and Eddy Current Exponents for Silicon Steel "), pp. 224-243, by Messrs. Charles P. Steinmetz, Henry Pikler, Ralph D. Mershon, William L. Puffer, A. S. McAllister, L. T. Robinson, George F. Seaver, J. R. Craighead, J. L. R. Hayden, F. M. Farmer, H. L. Schermerhorn, E. M. Hewlett, W. J. Foster, Charles F. Scott, C. A. Adams, and William A. Del Mar.

Relative merits of various methods of measuring of high e.m.f. Outline of proper method of insulating electrical machinery. Analytical study of stress distribution in cable insulation with proposed explanation of early breakdown in inner layers of insulation.

MECHANICAL FORCES IN MAGNETIC FIELDS

Charles P. Steinmetz **Vol. xxx—1911, pp. 367-385**

Elementary theory of the energy transformation in plunger magnets, giving equations for the mechanical work and the efficiency. Brief mathematical consideration of the mechanical forces exerted by short-circuit currents in transformers, cables and general circuits.

Discussion, pp. 386-413, by Messrs. A. S. McAllister, G. Faccioli, Cassius M. Davis, Mr. Harper, F. C. Green, C. J. Barrow, Henry Pikler, John J. Frank, Charles F. Scott, H. C. Cox, V. Karapetoff, K. Faye-Hansen, J. Murray Weed, H. B. Dwight, A. C. Zelewsky, E. Jasse and C. P. Steinmetz.

General discussion of the mechanical forces exerted on short circuits in transformers, equations, tests and experience. Energy transformations in plunger magnets.

THE REGULATION OF DISTRIBUTING TRANSFORMERS

C. E. Allen **Vol. xxx—1911, pp. 415-426**

Comparison of a number of the most important regulation formulas. Effect of different electric and magnetic constants upon regulation characteristics with varying power-factor. Modern winding construction for good regulation.

Discussion, incorporated with that of paper by F. C. Green on "Problems in the Operation of Transformers."

THE TEMPERATURE GRADIENT IN OIL IMMERSED TRANSFORMERS

James Murray Weed **Vol. xxx—1911, pp. 427-446**

General discussion of the complex temperature gradient from the hottest part of the transformer coil to the external air. Thermal properties of various substances. Laws of heat dissipation.

Discussion, incorporated with that of paper by F. C. Green on "Problems in the Operation of Transformers."

DISSIPATION OF HEAT FROM SELF-COOLED, OIL-FILLED TRANSFORMER TANKS

J. J. Frank and H. O. Stephens **Vol. xxx—1911, pp. 447-456**

Description of various modern types of transformer tanks, followed by results of tests bearing on the relative merits of each type in the dissipation of heat.

Discussion, incorporated with that of paper by F. C. Green on "Problems in the Operation of Transformers."

PROBLEMS IN THE OPERATION OF TRANSFORMERS

F. C. Green **Vol. xxx—1911, pp. 457-475**

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Discussion, (including that of paper by James Murray Weed on "The Temperature Gradient in Oil-Immersed Transformers" and paper by J. J. Frank and H. O. Stephens on "Dissipation of Heat from Self-Cooled, Oil-Filled Transformer Tanks"), pp. 476-494, by Messrs. W. S. Moody, Henry Pikler, E. G. Reed, Louis F. Blume, E. A. Wagner, C. A. Adams, A. E. Walden, Ralph D. Mershon, C. W. Stone, E. F. Alexanderson, C. P. Steinmetz, J. M. Weed, R. W. Atkinson and C. E. Allen.

General discussion of the regulation, cooling and protection of transformers from short-circuits.

COMMERCIAL TESTING OF SHEET IRON FOR HYSTERESIS LOSS

L. T. Robinson **Vol. xxx—1911, pp. 741-760**

Outline of the requirements of a shop method of testing iron. Description of testing outfits developed by the author, with results of tests of commercial iron. Relative accuracy and cost of testing compared with Epstein method.

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THE APPLICATION OF CURRENT TRANSFORMERS TO THREE-PHASE CIRCUITS

J. R. Craighead **Vol. xxx—1911, pp. 2167-2179**

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Discussion, incorporated with that of paper by Messrs. E. C. Stone and R. W. Atkinson on " Cost of Transformer Losses."

COST OF TRANSFORMER LOSSES

E. C. Stone and R. W. Atkinson **Vol. xxx—1911 pp. 2181-2199**

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Discussion, (including that of paper by J. R. Craighead on " The Application of Current Transformers to Three-Phase Circuits "), pp. 2200-2207, by Messrs. A. H. Pikler, W. C. Smith, E. A. Wagner, H. B. Gear, and R. W. Atkinson.

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MAGNETIC PROPERTIES OF IRON AT FREQUENCIES UP TO 200,000 CYCLES

E. F. W. Alexanderson **Vol. xxx—1911, pp. 2433-2448**

Measurements of magnetizing core loss and skin effect at high frequencies. Method of measuring power at high frequency. Relation between the various factors and frequency plotted as curves.

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Behavior of iron at high frequency.

9. ELECTRICAL MACHINERY AND APPARATUS

MECHANICAL FORCES IN MAGNETIC FIELDS

Charles P. Steinmetz **Vol. xxx—1911, pp. 367-385**

Elementary theory of the energy transformation in plunger magnets, giving equations for the mechanical work and the efficiency. Brief mathematical consideration of the mechanical forces exerted by short-circuit currents in transformers, cables and general circuits.

Discussion, pp. 386-413, by Messrs. A. S. McAllister, G. Faccioli, Cassius M. Davis, Harper, F. C. Green, C. J. Barrow, Henry

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General discussion of the mechanical forces exerted on short circuits in transformers, equations, tests and experience. Energy transformations in plunger magnets.

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H. A. Laycock **Vol. xxx—1911, pp. 555-571**

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FLYWHEEL LOAD EQUALIZER

W. N. Motter and L. L. Tatum **Vol. xxx—1911, pp. 729-739**

Description of a fly-wheel-generator installation designed to take the sudden peak loads encountered in the operation of ore bridges. Results of tests of power consumption and actual saving in the cost of handling the ore.

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THE USE OF POWER-LIMITING REACTANCES WITH LARGE TURBO-ALTERNATORS

R. F. Schuchardt and E. O. Schweitzer **Vol. xxx—1911, pp. 1143-1194**

Detailed account of exhaustive tests made to determine the action of reactors in the leads of turbo-generators under various conditions, with respect to the effect on the generators, on the secondary apparatus and on the stability of the system. Oscillograms of currents and e.m.fs. are given for each test. Bibliography.

Discussion, incorporated with that of paper by Charles P. Steinmetz on " Development of the Modern Central Station."

INDUCTION MACHINES FOR HEAVY SINGLE-PHASE MOTOR SERVICE

E. F. W. Alexanderson **Vol. xxx—1911, pp. 1357-1369.**

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AUTOMATIC MOTOR CONTROL FOR DIRECT-CURRENT MOTORS

Arthur C. Eastwood **Vol. xxx—1911, pp. 1519-1537**

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R. Wikander **Vol. xxx—1911, pp. 2019-2051**

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H. Weichsel **Vol. xxx—1911, pp. 2103-2124**

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Theodore Hoock **Vol. xxx—1911, pp. 2127-2158**

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E. F. W. Alexanderson **Vol. xxx—1911, pp. 2432-2448**

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Behavior of iron at high frequency.

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Gus A. Maier **Vol. xxx—1911, pp. 2455-2484**

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11. POWER PLANTS

COMMENTS ON FIXED COSTS IN INDUSTRIAL POWER PLANTS

John C. Parker **Vol. xxx—1911, pp. 637-652**

Analysis of fixed charges in isolated plants, covering investment, insurance, interest, depreciation, obsolescence, supervision, profit, real estate and space. Definition of marginal principle of figuring fixed cost.s Development of equation for amortization. Estimated and actual cost of energy production in isolated plants compared with central station service.

Discussion, incorporated with that of paper by Aldis E. Hibner on " The Cost of Industrial Power."

THE COST OF INDUSTRIAL POWER

Aldis E. Hibner **Vol. xxx—1911, pp. 653-664**

Brief consideration of the various factors that enter into the cost of energy production in isolated steam and gas producer plants. Effect of factory heating on cost of energy production. Investment, fixed charges and operating charges for heating plant, steam power plant and gas producer plant for a given industrial installation.

Discussion, (including that of paper by John C. Parker on " Comments on Fixed Costs in Industrial Power Plants ") pp., 665-727, by Messrs. A. M. Dudley, E. Richards, Ivar Lundgaard, A. S. L. Barnes, A. E. Hibner, A. L. Mudge, Percival Robert Moses, David B. Rushmore, R. P. Bolton, Arthur Williams, Parker H. Kemble, H. H. Edgerton, C. M. Ripley, H. W. Peck, John H. Norris, Richard H. Tillman, W. S. Timmis, Stonewall Tompkins, F. G. Gasche, William B. Jackson, R. Tschentscher, C. A. Graves, Frank F. Fowle, H. G. Gille, Thomas M. Gibbes, R. Norsa, Henry D. Jackson, Mr. Kelly, John West, C. A. Adams, J. F. Vaughan, Mr. Cook, Thomas M. Roberts, F. M. Gunby, J. C. Parker and Aldis E. Hibner.

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TRANSMISSION APPLIED TO IRRIGATION

O. H. Ensign and James M. Gaylord **Vol. xxx—1911, pp. 803-834**

Detailed description of the Minidoka and Salt River Projects of the Reclamation Service covering power houses, transmission lines and pumping stations.

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THE USE OF POWER-LIMITING REACTANCES WITH LARGE TURBO-ALTERNATORS

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DEVELOPMENT OF THE MODERN CENTRAL STATION

Charles P. Steinmetz **Vol. xxx—1911, pp. 1213-1225**

Short sketch of the development of modern alternating-current station. Uses to which reactors can be put in localizing disturbance in different parts of the system and improving parallel operation of units. Electromechanical synchronizing of distant stations.

Discussion, (including that of paper by R. F. Schuchardt and E. O. Schweitzer, "The Use of Power-Limiting Reactances with Large Turbo-Alternators" and paper by E. B. Merriam on "Some Recent Tests of Oil Circuit Breakers"), pp. 1226-1249, by Messrs. John W. Lieb, Jr., M. H. Collbohm, D. B. Rushmore, C. W. Stone, B. G. Lamme, W. L. Waters, J. J. Frank, Louis A. Ferguson, R. B. Williamson, Clarence P. Fowler, P. Junkersfeld and C. P. Steinmetz.

General remarks on problems in operation of very large central stations, with special reference to the use of reactance in the circuits.

12. PARALLEL OPERATION

DEVELOPMENT OF THE MODERN CENTRAL STATION

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General remarks on problems in operation of very large central stations, with special reference to the use of reactance in the circuits.

13. TRANSMISSION LINES

OPEN ATMOSPHERE AND DRY TRANSFORMER OIL AS HIGH-VOLTAGE INSULATORS

Harris J. Ryan **Vol. xxx—1911, pp. 1-76**

Analytical study of corona formation and the factors which influence it, covering practically all the work that has thus far been done by the author and other investigators. Complete references to all original work. Brief explanation of the ionization theory, which is applied to explain the phenomena that take place on high-tension lines. Laws formulated for calculation of critical e.m.f. under all conditions.

Discussion, incorporated with that of paper by E. L. West on "High-Voltage Line Loss Tests made on the 100-Kilovolt, 60-Cycle, 180-Mile Transmission Line of the Central Colorado Power Company."

HIGH-VOLTAGE LINE LOSS TESTS MADE ON THE 100-KILOVOLT, 60-CYCLE, 180-MILE TRANSMISSION LINE OF THE CENTRAL COLORADO POWER COMPANY

E. L. West **Vol. xxx—1911, pp. 77-85**

Communication to Professor Ryan by the author, giving detailed results of tests on extensive transmission system with and without load.

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DESIGN, CONSTRUCTION AND TEST OF AN ARTIFICIAL TRANSMISSION LINE

J. H. Cunningham **Vol. xxx—1911, pp. 245-256**

Detailed account of the mode of construction. Oscillograms of current and e.m.f. when the line was opened and closed.

Discussion, incorporated with that of paper by G. Faccioli on "Tests of Losses on High-Tension Lines."

PROTECTION OF ELECTRICAL TRANSMISSION LINES

E. E. F. Creighton **Vol. xxx—1911, pp. 257-326**

Comprehensive discussion of line disturbances due to arcing ground on insulated, dead-grounded and resistance-grounded systems, with description of arcing-ground suppressor and tests to which it has been submitted. Detailed treatment of line capacity under various conditions of grounding. General discussion of lightning disturbances. Theory of lightning induction. Elements in the design of transmission line that affect lightning disturbances. Arcing-over tests on insulators under various conditions. Profusely illustrated with photographs of arcs between lines, in horn gaps and over insulators, with oscillograms and circuit diagrams of the tests and of the arc suppressors.

Discussion, incorporated with that of paper by G. Faccioli on " Tests of Losses on High Tension Lines."

TESTS OF ARCING-GROUND SUPPRESSOR ON THE 40,000-VOLT SYSTEM OF THE SOUTHERN POWER COMPANY

C. I. Burkholder and R. H. Marvin **Vol. xxx—1911, pp. 327-335**

Description of tests of automatic insulator protector with high-power arcs for insulator. Circuit diagrams, photographs of arcs and oscillograms of potential rise and current.

Discussion, incorporated with that of paper by G. Faccioli on " Tests of Losses on High-Tension Lines."

TESTS OF LOSSES ON HIGH-TENSION LINES

G. Faccioli **Vol. xxx—1911, pp. 337-355**

Description of corona loss tests on lines of Central Colorado Power Company. Methods of measurements. Results in form of curves and in tables. Experimental law of corona loss. Equation of actual corona e.m.f. as function of spacing and diameter.

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Discussion of corona loss and critical e.m.f. laws. Experimental determinations. Actual distribution of insulator flash-overs among the three conductors of a three-phase line. Protection of lines from insulator spill-overs.

ECONOMIC LIMITATIONS TO AGGREGATION OF POWER SYSTEMS

Robert A. Philip **Vol. xxx—1911, pp. 597-630**

General discussion of the principles underlying the success of electric distribution of energy. Power diagrams developed for inter-connected distribution systems in which the e.m.f. at all generating and receiving stations is maintained constant by varying the reactive power in each receiving station. Numerical examples showing application of the line performance equations and vector diagrams.

Discussion, pp. 631-636, by Messrs. A. E. Kennelly, N. T. Wilcox, E. A. Ekern, Edw. N. Lake, and R. P. Jackson.

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TRANSMISSION APPLIED TO IRRIGATION

O. H. Ensign and James M. Gaylord **Vol. xxx—1911, pp. 803-834**

Detailed description of the Minidoka and Salt River Projects of the Reclamation Service, covering power houses, transmission lines and pumping stations.

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TRANSMISSION SYSTEMS FROM THE OPERATING STANDPOINT

R. J. C. Wood **Vol. xxx—1911, pp. 835-841**

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Discussion, (including that of paper by O. H. Ensign and James M. Gaylord on "Transmission Applied to Irrigation"), pp. 842-855, by Messrs. A. H. Babcock, C. L. Cory, E. F. Scattergood, Paul M. Downing, J. A. Lighthipe, Ralph Bennett, C. W. Koiner, L. J. Corbett, R. W. Sorensen, Ralph D. Mershon, O. H. Ensign and R. J. C. Wood.

Capital charges against irrigated land. Reliability of transmission systems.

CONTINUITY OF SERVICE IN TRANSMISSION SYSTEMS

Magnus T. Crawford **Vol. xxx—1911, pp. 1049-1071**

Brief description of Snoqualmie Falls transmission system, with outline of the general method of manipulation in the maintenance of service. Log of service interruptions covering period of four years and giving date, character, extent and cause of each disturbance. General discussion of causes of interruptions, and methods of avoiding them.

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Current practice in the operation of high-tension transmission systems.

ELECTRIC LINE OSCILLATIONS

G. Faccioli **Vol. xxx—1911, pp. 1803-1850**

Account of switching tests on 100,000-volt transmission system of the Great Western Power Company. Detailed discussion of large number of oscillograms. Recommendation for switching on high-tension systems. Appendix by W. W. Lewis on construction and operation of the photographic attachment to the oscillograph.

Discussion, pp. 1851-1856, by Messrs. C. P. Steinmetz, Max H. Collbohm, D. B. Rushmore and Percy H. Thomas.

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Percy H. Thomas **Vol. xxx—1911, pp. 1989-1993**

General discussion of answers to a list of questions submitted by the High-Tension Committee to companies operating transmission systems at 80,000 volts or more.

TRANSMISSION SYSTEM OF THE GREAT WESTERN POWER COMPANY

J. P. Jollyman **Vol. xxx—1911, pp. 1994-1997**

Answers to the list of questions submitted by the High-Tension Committee covering line construction, protection and operation at 100,000 volts.

Discussion, incorporated with that of paper by P. T. Hanscom on " Transmission System of the Central Colorado Power Company."

TRANSMISSION SYSTEM OF THE SOUTHERN POWER COMPANY

W. S. Lee **Vol. xxx—1911, pp. 1998-2001**

Answers to the list of questions submitted by the High-Tension Committee covering line construction, protection and operation at 100,000 volts.

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M. Hebgen **Vol. xxx—1911, pp. 2002-2006**

Answers to the list of questions submitted by the High-Tension Committee covering line construction, protection and operation at 100,000 volts.

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TRANSMISSION SYSTEM OF THE CENTRAL COLORADO POWER COMPANY

P. T. Hanscom **Vol. xxx—1911, pp. 2007-2014**

Answers to the list of questions submitted by the High-Tension Committee covering line construction, protection and operation at 100,000 volts. Detailed log of lightning disturbances.

Discussion, (including that of paper by J. P. Jollyman on " Transmission System of the Great Western Power Company," paper by W. S. Lee on " Transmission System of the Southern Power Company " and paper by M. Hebgen on " Transmission System of the Great Falls Power Company "), pp. 2015-2018, by Messrs. M. H. Collbohm, Paul M. Lincoln, L. C. Nicholson, N. J. Neall, J. F. Vaughan and Hugh Pastoriza.

General remarks on the protection of high-tension systems.

SOLUTION TO PROBLEMS IN SAGS AND SPANS

Wm. Le Roy Robertson **Vol. xxx—1911, pp. 2209-2228**

Comparison of the different types of equations for solution of sag problems. System of charts and tables for facilitating the calculation of sag in transmission wires.

Discussion, incorporated with that of paper by Pender and Thomson on " The Mechanical and Electrical Characteristics of Transmission Lines."

SAG CALCULATIONS FOR SUSPENDED WIRES

Percy H. Thomas **Vol. xxx—1911, pp. 2229-2239**

Short method of calculating sag. Description of use of method. Mathematical development of formulas.

Discussion, incorporated with that of paper by Pender and Thomson on " The Mechanical and Electrical Characteristics of Transmission Lines."

THE MECHANICAL AND ELECTRIC CHARACTERISTICS OF TRANSMISSION LINES

Harold Pender and H. F. Thomson **Vol. xxx—1911, pp. 2241-2279**

Equations and charts for calculation of the mechanical design of wire spans under various conditions of climate and topography. Equations, charts and tables for the calculation of the electrical performance of various types of transmission lines.

Discussion, (including " Solution to Problems in Sags and Spans " and " Sag Calculations for Suspended Wires "), pp. 2280-2302, by Messrs. Paul M. Lincoln, L. C. Nicholson, N. J. Neall, Jean Bart Balcomb, W. L. R. Robertson, H. F. Thomson, H. V. Carpenter, Hugh Pastoriza, R. S. Brown, Frank F. Fowle, R. C. Darrow, P. H. Thomas, Harold Pender and H. F. Thomson.

Calculation and design of transmission lines. Experience as to effects of wind, sleet and ice upon lines.

THE HIGH-EFFICIENCY SUSPENSION INSULATOR

A. O. Austin **Vol. xxx—1911, pp. 2303-2328**

Mathematical study of the efficiency of different shapes and types of suspension insulator. Judging an insulator by flash-over tests. Design of insulators for high tension.

Discussion, pp. 2329–2335, by Messrs. E. E. F. Creighton, Paul M. Lincoln, P. H. Thomas, E. M. Hewlett, N. J. Neall, A. O. Austin.

Behavior of insulators under high-tension stresses. Distribution of stresses between several parts of link insulators.

TABLES OF HYPERBOLIC FUNCTIONS IN REFERENCE TO LONG ALTERNATING-CURRENT TRANSMISSION LINES

A. E. Kennelly **Vol. xxx—1911, pp. 2495-2506**

Formula for use with hyperbolic functions in calculation of long transmission lines. Tables calculated for this purpose. Examples of the use of the formulas and tables in calculation of different types of lines. Bibliography of tables of complex hyperbolic functions.

No discussion.

14. ELECTRIC SERVICE DISTURBANCES AND PROTECTION

PROTECTION OF ELECTRICAL TRANSMISSION LINES

E. E. F. Creighton **Vol. xxx—1911, pp. 257-326**

Comprehensive discussion of line disturbances due to arcing ground on insulated, dead grounded and resistance grounded system, with description of arcing ground suppressor and tests to which it has been submitted. Detailed treatment of line capacity under various conditions of grounding. General discussion of lightning disturbances. Theory of lightning induction. Elements in the design of transmission line that affect lightning disturbances. Arcing-over tests on insulators under various conditions. Profusely illustrated with photographs of arcs between lines, in horn gaps and over insulators, with oscillograms and circuit diagram of the tests and of the arc suppressors.

Discussion, incorporated with that of paper by G. Faccioli on "Tests of Losses on High-Tension Lines."

TESTS OF ARCING GROUND SUPPRESSOR ON THE 40,000-VOLT SYSTEM OF THE SOUTHERN POWER COMPANY

C. I. Burkholder and R. H. Marvin **Vol. xxx 1911, pp. 327-335**

Description of tests of automatic insulator protector with high-power arcs for insulator. Circuit diagrams, photographs of arcs and oscillograms of potential rise and current.

Discussion, incorporated with that of paper by G. Faccioli on "Tests of Losses on High-Tension Lines."

CONTINUITY OF SERVICE IN TRANSMISSION SYSTEMS

Magnus T. Crawford **Vol. xxx—1911, pp. 1049-1071**

Brief description of Snoqualmie Falls transmission system, with outline of the general method of manipulation in the maintenance of service. Log of service interruptions covering period of four years and giving date, character, extent and cause of each disturbance. General discussion of causes of interruptions, and methods of avoiding them.

Discussion, pp. 1072-1079, by Messrs. R. J. C. Wood, P. M. Downing, E. F. Scattergood, G. H. Stockbridge, R. W. Van Norden, C. O. Poole, Ralph Bennett, D. D. Morgan, W. B. Gump and M. T. Crawford.

Current practice in the operation of high-tension transmission systems.

HIGH-TENSION TRANSMISSION

Percy H. Thomas **Vol. xxx—1911, pp. 1989-1993**

General discussion of answers to a list of questions submitted by the High-Tension Committee to companies operating transmission systems at 80,000 volts or more.

TRANSMISSION SYSTEM OF THE GREAT WESTERN POWER COMPANY

J. P. Jollyman **Vol. xxx—1911, pp. 1994-1997**

Answers to the list of questions submitted by the High-Tension Committee covering line construction, protection and operation at 100,000 volts.

Discussion, incorporated with that of paper by P. T. Hanscom on "Transmission System of the Central Colorado Power Company."

TRANSMISSION SYSTEM OF THE SOUTHERN POWER COMPANY

W. S. Lee **Vol. xxx—1911, pp. 1998-2001**

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M. Hebgen **Vol. xxx—1911, pp. 2002-2006**

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Discussion, (including that of paper by J. P. Jollyman on "Transmission System of the Great Western Power Company," paper by W. S. Lee on "Transmission System of the Southern Power Company" and paper by M. Hebgen on "Transmission System of the Great Falls Power Company"), pp. 2015-2018, by Messrs. M. H. Collbohm, Paul M. Lincoln, L. C. Nicholson, N. J. Neall, J. F. Vaughan and Hugh Pastoriza.

General remarks on the protection of high-tension systems.

15. DISTRIBUTION SYSTEMS

ADVANTAGES OF UNIFIED ELECTRIC SYSTEMS COVERING LARGE TERRITORIES

William B. Jackson **Vol. xxx—1911, pp. 131-151**

Statement of factors that make it economically possible to serve a large territory from one comprehensive transmission system. Maps and brief abstracts of a large number of hydroelectric and steam-electric distribution systems which cover extensive areas. Discussion of the advantages that a comprehensive system has over a large number of isolated small plants from the standpoint of economy and good service.

Discussion, pp. 152-165, by Messrs. P. Junkersfeld, W. L. Robb, F. Darlington, George H. Lukes, Norman T. Wilcox, Philip Torchio, L. L. Elden, Charles P. Steinmetz and William B. Jackson. General discussion of the advantages of a comprehensive distribution system over large territory and some of the factors that bear upon the success of such an undertaking. Actual comparison of the operation of the New York Edison plant with the London, Municipal and Private installations. Analysis of actual results obtained by the Boston Edison Company in the operation of a suburban system.

ECONOMIC LIMITATIONS TO AGGREGATION OF POWER SYSTEMS

Robert A. Philip **Vol. xxx—1911, pp. 597-630**

General discussion of the principles underlying the success of electric distribution of energy. Power diagram developed for inter-connected distribution systems in which the e.m.f. at all generating receiving stations is maintained constant by varying the reactive power in each receiving station. Numerical examples showing application of the line performance equations and vector diagrams.

Discussion, pp. 631-636, by Messrs. A. E. Kennelly, N. T. Wilcox, E. A. Ekern, Edw. N. Lake and R. P. Jackson.

General remarks on practicability of maintaining constant potential in all parts of a large system.

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Discussion, pp. 1072-1079, by Messrs. R. J. C. Wood, P. M. Downing, E. F. Scattergood, G. H. Stockbridge, R. W. Van Norden, C. O. Poole, Ralph Bennett, D. D. Morgan, W. B. Gump and M. T. Crawford.

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ELECTROLYTIC CORROSION IN REINFORCED CONCRETE

C. Edward Magnusson and C. H. Smith **Vol. xxx—1911, pp. 2055-2079**

Account of experimental investigation of damage done by stray currents in reinforced concrete. Study of various methods of protecting reinforcement from corrosion.

Discussion, pp. 2080-2101, by Messrs. Burton McCollum, E. W. Stevenson, G. D. Shepardson, George A. Hoadley, A. S. Langsdorf, Maxmilian Toch, Guy F. Shaffer, Harry Barker and W. L. Upson.

Description of similar investigations by the Bureau of Standards and others. Criticism of the authors' methods, especially of the high e.m.fs. used. Account of actual example of corrosion in a building.

THE APPLICATION OF CURRENT TRANSFORMERS TO THREE-PHASE CIRCUITS

J. R. Craighead **Vol. xxx—1911, pp. 2167-2179**

Analysis of the performance of series transformers with secondaries interconnected in various ways, the primaries being included in polyphase circuits.

Discussion, incorporated with that of paper by Messrs. E. C. Stone and R. W. Atkinson on " Cost of Transformer Losses."

COST OF TRANSFORMER LOSSES

E. C. Stone and R. W. Atkinson **Vol. xxx—1911, pp. 2181-2199**

Classification of transformer losses and complete analytical discussion of the cost of various losses under various operating conditions.

Discussion, (including that of paper by J. R. Craighead on " The Application of Current Transformers to Three-Phase Circuits ", pp. 2200-2207, by Messrs. A. H. Pikler, W. C. Smith, E. A. Wagner, H. B. Gear and R. W. Atkinson.

Progress in transformer design in a period of 12 years. Importance of long life as compared with energy efficiency.

16. CONTROL, REGULATION AND SWITCHING

HIGH-VOLTAGE LINE LOSS TESTS MADE ON THE 100-KILOVOLT, 60-Cycle, 180-MILE TRANSMISSION LINE OF THE CENTRAL COLORADO POWER COMPANY

E. L. West **Vol. xxx—1911, pp. 77-85**

Communication to Professor Ryan by the author, giving detailed results of tests on extensive transmission system with and without load.

Discussion, (including that of paper by Harris J. Ryan on "Open Atmosphere and Dry Transformer Oil as High Voltage Insulators"), pp. 86-130, by Messrs. M. I. Pupin, G. Faccioli, C. P. Steinmetz, William S. Stanley, J. B. Whitehead, Erich Hausmann, Samuel Sheldon, H. W. Fisher, J. E. Noeggerath, A. E. Kennelly, F. W. Peek, Jr., George L. Hoxie, A. B. Hendricks, Jr., J. A. Koontz, C. E. Bennett and Harris J. Ryan. General discussion of Professor Ryan's conclusions. Criticism and defense of electron theory. Formula for practical corona calculations on long distance lines. Method of constructing minute needle points. Relation between conductivity of gases and vapors and corona phenomena. Results of tests on high-tension lines and also with short spark discharge apparatus.

THE REGULATION OF DISTRIBUTING TRANSFORMERS

C. E. Allen **Vol. xxx—1911, pp. 415-426**

Comparison of a number of the most important regulation formulas. Effect of different electric and magnetic constants upon regulation characteristics with varying power-factor. Modern winding construction for good regulation.

Discussion, incorporated with that of paper by F. C. Green on "Problems in the Operation of Transformers."

OIL CIRCUIT BREAKERS

E. B. Merriam **Vol. xxx—1911 pp. 495-502**

Brief discussion of the functions and operative characteristics of automatic oil switches, and of factors which influence their performance.

Discussion, pp. 503-527, by Messrs. B. C. Jamieson, E. M. Hewlett, L. C. Nicholson, W. L. R. Emmet, R. D. Mershon, C. J. Barrow, H. W. Cheney, A. S. McAllister, Charles F. Scott, C. P. Steinmetz, H. L. Smith, E. W. Rice, Jr., E. B. Merriam, Chester Lichtenberg, A. G. Collis and E. Zachrisson.

Experience and tests with oil circuit breakers opening short-circuits. Theoretical analysis of the influence of different kinds of load upon rupturing capacity of oil switches.

VOLTAGE REGULATION OF GENERATORS

H. A. Laycock **Vol. xxx—1911, pp. 555-571**

Outline of requirements of generator and exciters essential to successful application of automatic regulation. Description of Tirrill regulator applied to alternating-current and direct-current systems. Examples of very large installations.

Discussion, pp. 572-573, by Messrs. H. G. Reist, Carl J. Fechheimer and E. F. Alexanderson.

Desirability of poor inherent regulation of large generators.

ECONOMIC LIMITATIONS TO AGGREGATION OF POWER SYSTEMS

Robert A. Philip **Vol. xxx—1911 pp. 597-630**

General discussion of the principles underlying the success of electric distribution of energy. Power diagram developed for inter-connected distribution systems in which the e.m.f. at all generating receiving stations is maintained constant by varying the reactive power in each receiving station. Numerical examples showing application of the line performance equations and vector diagrams.

Discussion, pp. 631-636, by Messrs. A. E. Kennelly, N. T. Wilcox, E. A. Ekern, Edw. N. Lake, R. P. Jackson.

General remarks on practicability of maintaining constant potential in all parts of a large system.

TRANSMISSION SYSTEMS FROM THE OPERATING STANDPOINT

R. J. C. Wood **Vol. xxx—1911, pp. 835-841**

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Discussion, (including that of paper of O. H. Ensign and James M. Gaylord on " Transmission Applied to Irrigation "), pp. 842-855, by Messrs. A. H. Babcock, C. L. Cory, E. F. Scattergood, Paul M. Downing, J. A. Lighthipe, Ralph Bennett, C. W. Koiner, L. J. Corbett, R. W. Sorensen, Ralph D. Mershon, O. H. Ensign and R. J. C. Wood.

Capital charges against irrigated land. Reliability of transmission systems.

CONTINUITY OF SERVICE IN TRANSMISSION SYSTEMS

Magnus T. Crawford **Vol. xxx—1911, pp. 1049-1071**

Brief description of Snoqualmie Falls transmission system, with outline of the general method of manipulation in the maintenance of service. Log of service interruptions covering period of four years and giving date, character, extent and cause of each disturbance. General discussion of causes of interruptions, and methods of avoiding them.

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THE USE OF POWER-LIMITING REACTANCES WITH LARGE TURBO-ALTERNATORS

R. F. Schuchardt and E. O. Schweitzer **Vol. xxx—1911, pp. 1143-1194**

Detailed account of exhaustive tests made to determine the action of reactors in the leads of turbo-generators under various conditions, with respect to the effect on the generators, on the secondary apparatus and on the stability of the system. Oscillograms of currents and e.m.fs. are given for each test. Bibliography.

Discussion, incorporated with that of paper by Charles P. Steinmetz on " Development of the Modern Central Station."

SOME RECENT TESTS OF OIL CIRCUIT BREAKERS

E. B. Merriam **Vol. xxx—1911 pp. 1195-1212**

Account of short-circuit rupturing tests with oil switch fed from a 12,000-kw. turbo-generator. Records of oil pressure generated, also e.m.f. and current oscillograms. Construction of oil switch to utilize the explosion energy.

Discussion, incorporated with that of paper by Dr. Charles P. Steinmetz on " Development of the Modern Central Station."

DEVELOPMENT OF THE MODERN CENTRAL STATION

Charles P. Steinmetz **Vol. xxx—1911, pp. 1213-1226**

Short sketch of the development of modern alternating-current station. Uses to which reactors can be put in localizing disturbance in different parts of the system and improving parallel operation of units. Electromechanical synchronizing of distant stations.

Discussion. (including that of paper by R. F. Schuchardt and E. O. Schweitzer " The Use of Power-Limiting Reactances with Large Turbo-Alternators and paper by E. B. Merriam on " Some Recent Tests of Oil Circuit Breakers "), pp. 1226-1249, by Messrs. John W. Lieb, Jr., M. H. Collbohm, D. B. Rushmore, C. W. Stone, B. G. Lamme, W. L. Waters, J. J. Frank, Louis A. Ferguson, R. B. Williamson, Clarence P. Fowler, P. Junkersfeld and C. P. Steinmetz.

General remarks on problems in operation of very large central stations, with special reference to the use of reactance in the circuits.

AUTOMATIC MOTOR CONTROL FOR DIRECT-CURRENT MOTORS

Arthur C. Eastwood **Vol. xxx—1911, pp. 1519-1537**

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Experience in the design of series current-control contactors.

SOME LIMITATIONS OF RHEOSTATIC CONTROL

G. R. Radley and L. L. Tatum **Vol. xxx—1911, pp. 1547-1561**

Discussion of the factors that influence the design of resistors for different classes of service. Data on heating and limiting temperatures for resistance terminals and contacts.

No discussion.

ELEVATOR CONTROL

T. E. Barnum **Vol. xxx—1911, pp. 1563-1583**

Brief description of the construction and performance of typical passenger elevator electric motive power equipment. Photographs, connections diagrams and current-time performance curves.

Discussion, pp. 1584-1585, by Messrs. Fred J. Newman, S. N. Clarkson, Theodore Varney and T. E. Barnum.

Efficiency of worm gears.

ELECTRIC LINE OSCILLATIONS

G. Faccioli **Vol. xxx—1911, pp. 1803-1850**

Account of switching tests on 100,000-volt transmission system of the Great Western Power Company. Detailed discussion of large numbers of oscillograms. Recommendation for switching on high-tension systems. Appendix by W. W. Lewis on construction and operation of the photographic attachment to the oscillograph.

Discussion, pp. 1851-1856, by Messrs. C. P. Steinmetz, Max H. Collbohm, D. B. Rushmore and Percy H. Thomas.

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Percy H. Thomas **Vol. xxx—1911, pp. 1989-1993**

General discussion of answers to a list of questions submitted by the High-Tension Committee to companies operating transmission systems at 80,000 volts or more.

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Calculation and design of transmission lines. Experience as to effects of wind, sleet and ice upon lines.

METHODS OF VARYING THE SPEED OF ALTERNATING-CURRENT MOTORS

Gus A. Maier **Vol. xxx—1911, pp. 2455-2484**

Classification of types of varying and adjustable speed alternating-current motors. Comprehensive description of various types of speed control for induction and commutator motors, including rheostatic, compensator, brush shifting, pole changing, concatenation, frequency changer and regulating motors.

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Description of additional methods of speed variation.

17. TRACTION

SOME RECENT DEVELOPMENTS IN RAILWAY TELEPHONY

Gregory Brown **Vol. xxx—1911, 1007-1036**

Outline of requirements of train dispatching service, messenger service and block service. Description of various telephone systems in use on railroads. Photographs of apparatus and circuit diagrams.

Discussion, pp. 1037-1048, by Messrs. Kempster B. Miller, L. B. Cramer, Ralph Bennett, Ralph W. Pope, C. F. Elwell, S. G. McMeen, J. A. Lighthipe, S. J. Lisberger and Gregory Brown.

Experience with telephony in operation of railway and transmission systems.

INDUCTION MACHINES FOR HEAVY SINGLE PHASE MOTOR SERVICE

E. F. W. Alexanderson **Vol. xxx—1911, pp. 1357-1369**

Description, theory and performance characteristics of phase converter for changing single-phase to polyphase energy.

Discussion, incorporated with that of paper by William S. Murray on "Electrification Analyzed, and Its Practical Application to Trunk Line Roads, Inclusive of Freight and Passenger Operation."

ELECTRICAL OPERATION OF THE WEST JERSEY AND SEASHORE RAILROAD

B. F. Wood **Vol. xxx—1911, pp. 1371-1390**

Brief description of electric system and equipment. Cost of construction, maintenance and operation charges in detailed tabular form, and logs of repairs and train detentions.

Discussion, incorporated with that of paper by William S. Murray on "Electrification Analyzed, and Its Practical Application to Trunk Line Roads, Inclusive of Freight and Passenger Operation."

ELECTRIFICATION ANALYZED AND ITS PRACTICAL APPLICATION TO TRUNK LINE ROADS, INCLUSIVE OF FREIGHT AND PASSENGER OPERATION

William S. Murray **Vol. xxx—1911, pp. 1391-1456**

Analysis of passenger, freight and switching service of steam locomotives. Performance and economy tests. Characteristics and advantages of electric locomotives for the same classes of service. Statistical record of operation of New Haven Road, covering train delays, power house, distribution systems and locomotives. Wiring diagrams and constructional drawings for locomotives and distribution system. Cost data for electrification of railroads.

Discussion, (including that of paper by E. F. W. Alexanderson on "Induction Machines for Heavy Single-Phase Motor Service" and paper by B. F. Wood on "Electrical Operation of the West Jersey and Seashore Railroads"), pp. 1457-1518, by Messrs. Frank J. Sprague, Edwin B. Katte, L. C. Fritch, J. L. Woodbridge, Dugald C. Jackson, N. W. Storer, John W. Lieb, Jr., Charles F. Scott, E. F. W. Alexanderson, Philip Dawson, W. N. Smith, B. F. Wood, John B. Taylor, R. E. Hellmund, C. P. Steinmetz, H. Graftio, Gisbert Kapp and W. S. Murray.

General discussion of the problem of equipping trunk lines with electric motive power. Experience with direct-current and single-phase systems. Standardization of electric apparatus.

ELECTROLYTIC CORROSION IN REINFORCED CONCRETE

C. Edward Magnusson and C. H. Smith **Vol. xxx—1911, pp. 2055-2079**

Account of experimental investigation of damage done by stray currents in reinforced concrete. Study of various methods of protecting reinforcement from corrosion.

Discussion, pp. 2080-2101, by Messrs. Burton McCollum, E. W. Stevenson, G. D. Shepardson, George A. Hoadley, A. S. Langsdorf, Maxmilian Toch, Guy F. Shaffer, Harry Barker and W. L. Upson.

Description of similar investigations by the Bureau of Standards and others. Criticism of the author's methods, especially of the high e.m.fs. used. Account of actual example of corrosion in a building.

18. LIGHT, LIGHTING AND LAMPS

THE COST OF ARC LIGHTING AND GENERAL SERVICE FROM MEDIUM AND SMALL SIZE MUNICIPAL OR PRIVATE PLANTS

W. Edgar Reed **Vol. xxx—1911, pp. 1121-1133**

Analysis of cost of lighting small communities. Character of various items that enter into the construction and conditions which modify them. Actual cost of lighting different cities.

No discussion.

19. ELECTRICITY IN THE ARMY AND NAVY

PROPOSED APPLICATIONS OF ELECTRIC SHIP PROPULSION

W. L. R. Emmet **Vol. xxx—1911, pp. 529-544**

Reasons why electric propulsion of ships is practicable. Description of two proposed turbo-electric installations for United States warships. Characteristic performance curves and economy of electric equipments.

Discussion, pp. 545-554, by Messrs. C. P. Steinmetz, Gano Dunn, Maxwell W. Day, W. B. Potter, H. A. Mavor, and C. H. Peabody and H. G. Knox.

Power requirements of battleships and advantages of electric propulsion.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

MECHANICAL FORCES IN MAGNETIC FIELDS

Charles P. Steinmetz **Vol. xxx—1911, pp. 367-385**

Elementary theory of the energy transformation in plunger magnets, giving equations for the mechanical work and the efficiency. Brief mathematical consideration of the mechanical forces exerted by short-circuit currents in transformers, cables and general circuits.

Discussion, pp. 386-413, by Messrs. A. S. McAllister, G. Faccioli, Cassius M. Davis, Mr. Harper, F. C. Green, G. J. Barrow, Henry Pikler,, John J. Frank, Charles F. Scott, H. C. Cox, V. Karapetoff, K. Faye-Hansen, J. Murray Weed, H. B. Dwight, A. C. Zelewsky, E. Jasse and C. P. Steinmetz.

General discussion of the mechanical forces exerted on short circuits in transformers, equations, tests and experience. Energy transformations in plunger magnets.

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FLYWHEEL LOAD EQUALIZER

W. N. Motter and L. L. Tatum **Vol. xxx—1911, pp. 729-739**

Description of a flywheel-generator installation designed to take the sudden peak loads encountered in the operation of ore bridges. Results of tests of power consumption and actual saving in the cost of handling the ore.

No discussion.

TRANSMISSION APPLIED TO IRRIGATION

O. H. Ensign and James M. Gaylord **Vol. xxx—1911, pp. 803-834**

Detailed description of the Minidoka and Salt River Projects of the Reclamation Service, covering power houses, transmission lines and pumping stations.

Discussion, incorporated with that of paper by R. J. C. Wood on " Transmission Systems from the Operating Standpoint."

TRANSMISSION SYSTEM FROM THE OPERATING STANDPOINT

R. J. C. Wood **Vol. xxx—1911, pp. 835-841**

Requirements of good service on high-tension transmission systems—regulation, reliability.

Discussion, (including that of paper by O. H. Ensign and James M. Gaylord on " Transmission Applied to Irrigation "), pp. 842-855, by Messrs. A. H. Babcock, C. L. Cory, E. F. Scattergood, Paul M. Downing, J. A. Lighthipe, Ralph Bennett, C. W. Koiner, L. J. Corbett, W. R. Sorensen, Ralph D. Merson, O. H. Ensign and R. J. C. Wood.

Capital charges against irrigated land. Reliability of transmission systems.

THE REFINING OF IRON AND STEEL IN INDUCTION TYPE FURNACES

C. F. Elwell **Vol. xxx—1911, pp. 857-866**

Brief discussion of the relative merits of arc and induction furnaces and the leading characteristics of each. Analyses of steel produced and itemized cost of production in different sized induction furnaces.

Discussion, pp. 867-871, by Messrs. R. J. C. Wood, R. W. Van Norden, Earl W. Paul, J. J. Frank, H. H. Sinclair, R. W. Sorensen, C. W. Koiner, Budd Frankenfield, C. H. Vom Baur and C. F. Elwell.

Data on methods and cost of operating electric furnaces.

ELEVATOR CONTROL

T. E. Barnum **Vol. xxx—1911, pp. 1563-1583**

Brief description of the construction and performance of typical passenger elevator electric motive power equipment. Photographs, connections diagrams and current-time performance curves.

Discussion, pp. 1584-1585, by Messrs. Fred J. Newman, S. N. Clarkson, Theodore Varney and T. E. Barnum.

Efficiency of worm gears.

ELECTRICALLY DRIVEN REVERSING ROLLING MILLS

Wilfred Sykes **Vol. xxx—1911, pp. 1587-1605**

Advantages of reversing mill over three-high mill. General discussion of the problem of driving reversing mills. Power requirements and methods of speed control. Design data for control apparatus and flywheels. Description of reversing mill of Illinois Steel Company.

Discussion, pp. 1606-1616, by Messrs. Karl A. Pauly, F. G. Gasche, R. Tschentscher, Theodore Hoock, Wilfred Sykes.

General discussion of the relative merits of reversing two-high and non-reversing three-high mills.

ELECTRICITY IN THE LUMBER INDUSTRY

Edward J. Barry **Vol. xxx—1911, pp. 1081-1085**

General outline of the uses to which electric energy can be put in the logging and lumber industry.

Discussion, pp. 1086-1088, by Messrs. R. L. Noggle, J. A. Lighthipe, C. Pemschel and Ralph Bennett.

Power required by lumber machinery.

21. TELEPHONY AND TELEGRAPHY

NEW AUTOMATIC TELEPHONE EQUIPMENT

Charles S. Winston **Vol. xxx—1911, pp. 915-937**

Description of construction and mode of operation of new automatic telephone switching apparatus. Photographs and connection diagrams.

Discussion, incorporated with that of paper by Edward E. Clement on " The Semi-Automatic Method of Handling Telephone Traffic."

THE SEMI-AUTOMATIC METHOD OF HANDLING TELEPHONE TRAFFIC

Edward E. Clement **Vol. xxx—1911, pp. 939-974**

Description of authors semi-automatic " clearing-house " method of operating telephone switchboard. Discussion of the relative merits of manual, automatic and semi-automatic systems. Study of the savings in time, money and space that can be effected by substituting semi-automatic for manual telephone systems.

Discussion, (including that of paper by C. S. Winston on New Automatic Telephone Equipment) pp. 975-1005, by Messrs. J. W. Gilkyson, Mr. Keller, K. B. Miller, A. H. Griswold, A. H. Babcock, Ralph W. Pope, F. C. Newell, Jr., Ralph Bennett, W. D. Moore, Mr. Schuler, H. B. Tupper, C. L. Cory, Arthur Bessey Smith, Henry P. Clausen, C. S. Winston and E. E. Clement.

General remarks on the relative merits of automatic, semi-automatic and manual telephone systems, experience with automatic and semi-automatic systems.

SOME RECENT DEVELOPMENTS IN RAILWAY TELEPHONY

Gregory Brown **Vol. xxx—1911, pp. 1007-1036**

Outline of requirements of train dispatching service, messenger service and block service. Description of various telephone systems in use on railroads. Photographs of apparatus and circuit diagrams.

Discussion, pp. 1037-1048, by Messrs. Kempster B. Miller, L. B.

Cramer, Ralph Bennett, Ralph W. Pope, C. F. Elwell, S. G. McMeen, J. A. Lighthipe, S. J. Lisberger and Gregory Brown.

Experience with telephony in operation of railway and transmission systems.

MULTIPLEX TELEPHONY AND TELEGRAPHY BY MEANS OF ELECTRIC WAVES GUIDED BY WIRES

George O. Squier **Vol. xxx—1911, pp. 1617-1665**

Account of exhaustive investigation of transmission of high-frequency energy over existing telephone and telegraph circuits, superimposing the high-frequency energy on the telephone energy without interference. Use of wireless sending and receiving apparatus on wire lines. Connection diagram, resonance and other performance curves from tests.

Discussion, pp. 1666-1681, by Messrs. Frank B. Jewett, E. F. W. Alexanderson, John B. Taylor, S. G. McMeen, Frank F. Fowle, Bela Gati.

Commercial adaptability of author's system. Measurements on high-frequency circuits.

TELEGRAPH TRANSMISSION

Frank F. Fowle **Vol. xxx—1911, pp. 1683-1738**

Mathematical theory of telegraph transmission. General equations developed and applied to simplex, duplex and quadruplex systems. Discussion of changes in relays, terminal relays and line insulators that will improve transmission. Effect of various factors on transmission presented in tabular form.

Discussion, pp. 1739-1741, by Messrs. Bancroft Gherardi and Frank F. Fowle.

Choice of insulator and conductor material for telegraph line construction.

THE COMMERCIAL LOADING OF TELEPHONE CIRCUITS IN THE BELL SYSTEM

Bancroft Gherardi **Vol. xxx—1911, pp. 1743-1764**

Brief statement of the formulas used in calculating transmission over loaded lines. Methods used and results attained in the loading of overhead lines and underground cables. Construction of loading coils. Effect of loading in modifying telephone practice.

Discussion, pp. 1765-1773, by Messrs. E. H. Bangs, F. B. Jewett, E. H. Colpitts, E. B. Craft, Allard Smith, J. G. Wray, Frank F. Fowle, Bancroft Gherardi and G. D. Shepardson.

Changes brought about in terminal apparatus and outside plant by loading lines. Difficulties involved in the development of practical methods of loading.

PROBLEMS IN TELEPHONE TRAFFIC ENGINEERING

F. P. Valentine **Vol. xxx—1911, pp. 1175-1796**

Discussion of the factors that make up good service. Relative efficiency of different methods of handling traffic, with special reference to toll.

Discussion, pp. 1797-1801, by Messrs. A. P. Allen, W. Lee Campbell, Bancroft Gherardi and F. P. Valentine.

Efficiency of telephone apparatus.

22. MISCELLANEOUS TOPICS AND INSTITUTE AFFAIRS

ELECTRICAL ENGINEERS AND THE PUBLIC

PRESIDENT'S ADDRESS

Dugald C. Jackson **Vol. xxx—1911, pp. 1135-1142**

The duties of the engineer to the public, with special regard to his attitude toward public service corporations.

No discussion.

RESPONSIBILITIES OF ELECTRICAL ENGINEERS IN MAKING APPRAISALS

H. M. Byllesby **Vol. xxx—1911, pp. 1251-1265**

Developments of electrical industry. Part played by capital in the development of electric public utilities. Intangible values to be considered in the valuation of such properties.

Discussion, incorporated with that of paper by Henry Floy on " Depreciation as Related to Electrical Properties."

DEPRECIATION AS RELATED TO ELECTRICAL PROPERTIES

Henry Floy **Vol. xxx—1911, pp. 1267-1309**

Definition of terms entering into depreciation. Classification of factors that make up depreciation. Explanation of various methods of calculating depreciation. Tabulated cases of depreciation rates used by different authorities. Method of determining value of physical properties. Use of 50 per cent method.

Discussion, (including that of paper by H. M. Byllesby on " Responsibilities of Electrical Engineers in Making Appraisals "), pp. 1310-1356, by Messrs. Bion J. Arnold, W. F. Wells, J. W. Lieb, Jr., Schuyler S. Wheeler, E. Leonarz, G. L. Hoxie, P. H. Thomas, W. A. Del Mar, F. W. Harris, Horatio A. Foster, J. G. Hirsch, Alten S. Miller, Frank F. Fowle, B. E. Sunny, Halbert P. Gillette and Henry Floy.

General discussion of depreciation and the appraisal of public utilities.

TURIN MEETING OF THE INTERNATIONAL ELECTROTECHNICAL COMMISSION SEPTEMBER 7-13, 1911

Vol. xxx—1911, pp. 2507-2518

Provisional report from the United States National Committee to the Board of Directors covering history of International Electrical Congress, organization of Congress, and brief notes on the sessions at the Turin meeting.

THE INTERNATIONAL ELECTROTECHNICAL CONGRESS OF TURIN

Vol. xxx—1911, pp. 2519-2533

Report of the American Institute of Electrical Engineers Delegation to the Board of Directors, covering organization, list of delegates and list of reports and papers presented.

STANDARDIZATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Vol. xxx—1911, pp. 2535-2585

Standardization rules of Institute with International rules approved by the Turin Congress.

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1911

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Report of the Board of Directors and various committees.

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OPEN ATMOSPHERE AND DRY TRANSFORMER OIL AS HIGH-VOLTAGE INSULATORS[†]

BY HARRIS J. RYAN

I. Cause of the Great Dielectric Strength of Air Films on the Surface of a Conductor at High-potential

a. By the method that employs a conductor of circular section mounted in the air at the center of a hollow conducting cylinder, the electric stresses at the conductor surface required to start corona were observed and reported to the Institute.[*] These observations are recharted, using kilovolts per inch, in lieu of coulombs per inch-cube, for the stresses, so as to locate the single curve, drawn in Figs. 1*a* and 1*b*. These data apply to the normal indoor atmosphere at a temperature of 70 deg. fahr., barometer of 29.5 in. (750 mm.) and an elevation of 850 ft. (259 m.) above sea level. The galvanized sheet iron cylinder was new and clean, 3 ft. (91.4 cm.) long, 15 in. (38 cm.) diameter and *open at both ends*. Approximate sine-wave, 133-cycle, high-voltage alternating e.m.fs. applied the electric stresses between the conductors and the cylinder. The maximum values of these e.m.fs. were checked by needle spark-gaps. The conductors were clean brass rods for the *one quarter inch* (6.35 mm.) and larger diameters, and clean copper wires for the smaller diameters.[‡] The work was done indoors and at night to facilitate visual observation of the *complete corona-start*. The size of the room employed was approximately 40 by 40 by 15 ft. (12.2 by 12.2 by 4.5 m.), and the air in it reasonably dust free due to ordinary settling. The ions and radioactivity present in the air were not observed because their existence and importance in corona formation were not understood at the time.

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[*] The Conductivity of the Atmosphere at High Voltages, Harris J. Ryan. Transactions A. I. E. E., Vol. XXI, p. 275, 1904.

[†] A paper submitted to the A. I. E. E. through the San Francisco Section, for the January 13, 1910 meeting at New York.

[‡] The term clean here means ordinarily clean and not "*clean*" a present day corona term.

In the former paper it was shown that the relation of these surface stresses to the corresponding conductor diameters was such as to point strongly to the existence of a dielectrically stout thin film of air next to the conductor surfaces as suggested earlier by Steinmetz. The envelope method was employed to locate the distances from the surfaces of the conductor to the zone whereat the air behaved the weakest in relation to the diminishing radial stresses. For sizes above one-quarter inch this distance to the zone of supposed initial rupture was found to be

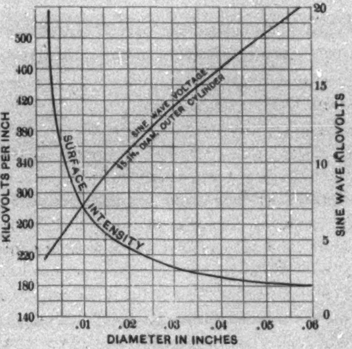

FIG. 1*a*

nearly uniform at about 0.07 in. (1.78 mm.); the corresponding rupturing stress was found to be 76 kilovolts per in., or 30 kilovolts per cm. The fact that in a particular case the corona starts with a definite minimum radial thickness and that this thickness ends at an outer radial stress of 76 kilovolts per in. was considered to be highly significant of the character of the strong air film; more especially so because this stress is the same as that required to rupture air in a uniform field between two parallel plate electrodes according to J. J. Thomson and other authorities on the conduction of electricity through gases. It indicated that initial corona is dependent not only on the application of a certain minimum stress but also upon a certain minimum *striking distance* through which such stress must be applied. As the stress about the charged conductor is radial in direction its density diminishes as the distance from the surface increases. Within the zone 0.07 in. (1.78 mm.) from the surface of the conductor at which the corona forming critical stress is 76 kilovolts per in. the average stress is, therefore, higher. It appeared reasonable to expect if this *striking distance is* necessary that it would be shorter for smaller diameters and longer for the larger diameters, though the relation might not be one of direct proportion.

With the smaller diameters owing to the greater rate of spread of the stress as it extends from the surface of the conductor, the average stress applied between the surface of the conductor and the zone of critical stress, 76 kilovolts per in. would be greater, the *corona striking* effect would be greater, making it possible to start corona through a shorter minimum range of action. For the same reason larger diameters should employ somewhat greater striking distances. With the larger diameters, however, the spread of the stress is far more gradual which results in a relatively smaller increase in striking distance with increase in diameters. Below one-quarter inch the envelope method had given results that were anomalous. It now seemed reasonable to expect that these anomalies were due principally to the graphical errors that can hardly be avoided for the small di-

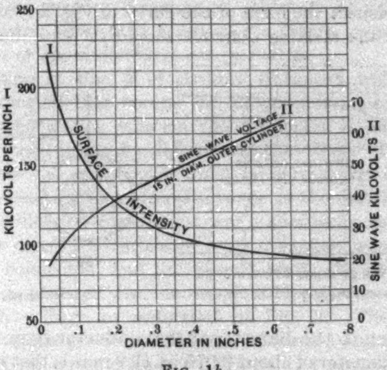

FIG. 1*b*

ameters, and that the coronas about such small diameters started in the same manner as in the case of the larger diameters, *viz.*, by a certain striking distance that terminates at the critical stress, 76 kilovolts per in.

It was evident, if this view is correct, that the critical stress zone, 76 kilovolt per in., should be found in each case at a certain distance from the conductor surface in initial corona formation, that in applying this test in Fig. 1, the striking distances for the various diameters should have a continuous relation and correspondingly locate a curve of striking distances and diameters that should have a rational character throughout the whole range of conductor sizes. The curve in Fig. 2 was thus located from the data curve in Fig. 1*a* and 1*b*.

In one respect the form of the curve in Fig. 2 is at first a surprise, that the striking distance should increase almost exactly in proportion to the diameter of the conductor from the smallest sizes to a diameter of about 0.075 in. (1.9 mm.); that immediately beyond this diameter and thereafter the striking distances increase very slowly with the diameter, attaining a value of 0.07 in. (1.78 mm.) at a diameter of 0.5 in. (12.7 mm.) and finally a value of about 0.25 in. (6.35 mm.) at a very great diameter. This sudden bend in the curve occurs at the diameter whereat the corona even under the influence of an ideally uniform radial electric field does not form uniformly; it starts in a patchy fashion. It has been observed that the factors that determine whether the corona will or will not start uniformly over the entire surface of the conductor are dependent upon:

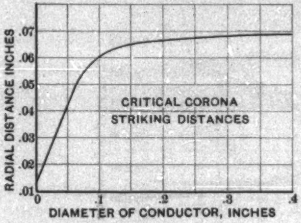

FIG. 2

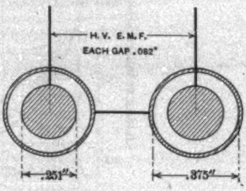

FIG. 3

1. The density of the gas, *i.e.*, upon its temperature and pressure.
2. Upon the degrees of uniformity of the electric stress producing the corona.

3. The spread of the electric stress in the air about the conductor and, therefore, upon the radius of curvature of the conductor.

These factors come into effect in such a manner for air at normal temperature and pressure when the striking distance attains a value of about 0.055 to 0.060 in. (1.39 to 1.52 mm.) for conductor diameters of 0.075 in. to 0.10 in. (1.9 to 2.5 mm.), such that thereafter the aggregate striking distances increase very slowly with increase in diameters. At these diameters above 0.10 in. (2.5 mm.) uniform corona never starts in air at normal density. It always makes an irregular start.

b. Experiments above, below, and at normal atmospheric pressure sustaining the view that corona and spark-discharges require certain critical striking distances in which to be established at minimum stress; below these distances the stresses required to produce coronas or spark-discharge are increased.

The relation in Fig. 2 of striking distances and diameters strongly indicated that corona for all cases is simply a spark-discharge phenomenon wherein the conductor is one electrode and the air conducting by *diffusion* is the other. Under these circumstances the spark itself must be spread out quite fully, completely resulting in a glow-discharge of the familiar corona. The first verification experiment was undertaken as follows:

Two pair of concentric clean brass cylinders were provided, electrically connected, and the normal air in the gaps between the cylinders stressed by the application of sine-wave alternating high voltage as indicated in Fig. 3. The diameters of the inner cylinders were 0.251 in. (6.35 mm.) and the internal diameters of the outer cylinders 0.375 in. (9.4 mm.), so that the radial depths of air between the conducting cylinders was 0.062 in. (1.5 mm.) which is nearly equal to the corresponding striking distance, 0.066 in. (1.67 mm.) given by the curve in Fig. 2 for a diameter of 0.251 in. (6.35 mm.). It was found in this experiment that the alternating voltages that produced a pair of sparks in series from cylinder to cylinder across the source terminals also produced a stress of 76 kilovolts per in. at the inner surfaces of the outer cylinders. One pair of cylinders was cut out and the high voltage applied to the remaining pair. It was then found that exactly *one-half* of the former voltage had to be applied to establish a single discharge between one pair of cylinders. The stress at the inner surface of the outer cylinder was 76 kilovolts per in. as before. Thus the identity of corona and a spark discharge between conductors at corresponding electric stresses was established.

If the critical striking distance required for initial corona formation at minimum voltage is due to the *headway* requirements of *ionization by collision*, the variation of the pressure of the air in which the concentric cylinders are mounted should from general knowledge be equivalent to a certain corresponding variation of the length of the air gap between the cylinders. A pair of the above cylinders was placed under a large bell-jar of a laboratory air pump. The above experiment was repeated at various pneumatic pressures below and above that of the normal atmosphere. The relation obtained between the approximate sine-wave 60-cycle alternating voltage and the air pressure in inches of mercury at which the discharges occurred were used to locate curve *I* in Fig. 4. Below one atmosphere, 29.5 in. (750 mm.) of mercury, the relation is curvelinear and above that pressure, rectilinear. This result means that at one atmosphere the critical striking distance is just equal to the

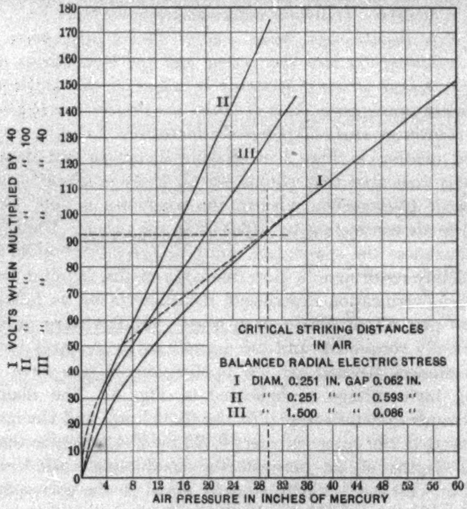

FIG. 4

depth of the air gap between the cylinders; above one atmosphere the critical striking distance is shorter and below one atmosphere it is longer than the air gap. When the critical striking distance is longer than the distance between the electrodes the critical stress zone, 76 kilovolts per in., falls beyond the inner surface of the outer cylinder, a higher average stress and, therefore, voltage, must be applied to make up for the lack of headway required to start the spark. Starting at a low value of air pressure, the voltage rises at a more rapidly diminishing rate than the air pressure because the shortage in headway required for sparking at minimum stress is constantly diminishing. At one atmosphere the shortage in required striking distance has just disappeared, and after that the air pressure and sparking voltage increase in direct proportion. It is obvious that when the shortage in striking distance disappears there should be a change in the relation of voltage to air pressure but it is not just yet obvious that it should be the law of direct proportion. We will return to a consideration of this later on. To check such an understanding of these matters further and to show that the striking distance just equaled the air gap at one atmosphere because it was chosen in conformity with the relation in Fig. 2, gaps were provided between two pairs of concentric cylinders having diameters differing from those employed above. Cross sections of these cylinders with their dimensions are given in Fig. 5. The experiment recorded in curve *I*, Fig. 4, was repeated with each of these pairs of concentric cylinders and the results located curves *II* and *III*, Fig. 4. In each of these cases the depth of air gaps were chosen so as not to conform with the striking distance and their corresponding conductor diameters found in Fig. 2. The changes from curve to right line in the sparking-voltage to air-pressure relations as found for these two cases occur at pressures differing from one another and from that of the normal atmosphere just as should be the case if the above view is correct.

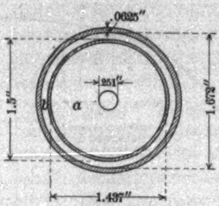

FIG. 5

The curves given in Fig. 4 have a bearing upon the manner in which corona forming voltage will vary with barometric pressure and, therefore, with altitude; this will be referred to later on.

*c. Confirmation results obtained by Baille, Paschen and Schuster**

Many years ago Baille and Paschen by means of continuous e.m.fs. observed with great care the voltages required to spark through various distances of normal indoor atmosphere between metal spheres of various diameters and between parallel metal plates. Later on Schuster calculated the corresponding electric stresses at the surface of the spherical and plane electrodes. His results stood originally in c.g.s. units. They have been re-expressed in kilovolts per in., for surface stress and inches for distance in Fig. 6.

We can readily make a mental picture of the electric fields between pairs of concentric cylinders, spheres and parallel planes. Invoking our judgment we can compare mentally the modern results by concentric cylinders in producing coronas and related spark-discharges with the old Baille-Paschen-Schuster results obtained by sparking between pairs of spheres and parallel plates. In doing this we find a practical agreement throughout. Between concentric cylinders the electric field spreads uniformly; between spheres it spreads more rapidly to the mid-point and then contracts in the same fashion to the near surface of the opposite sphere. The differences between these two classes of fields are largely of a compensating character,

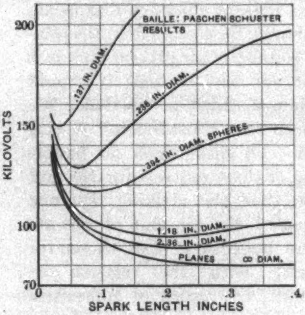

FIG. 6

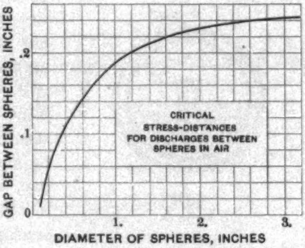

FIG. 7

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*Baille, Annales de Chemie et de Physique XXV p. 486, 1882; Paschen, Wied. Ann. XXXVII p. 79, 1889; Schuster, Phil. Mag. V. 29, p. 182, 1890; and quoted by J. J. Thomson, Conduction of Electricity through Gases, first edition p. 287–9.

so that in *voltage—distance* effects they are not widely different after all. The fields between parallel planes are simply special cases of either the concentric cylinders or opposing spheres wherein the diameters are infinite. It must follow, therefore, that a curve located by the Baille-Paschen-Schuster values of diameters and the corresponding striking distances at minimum surface stress should be reasonably in accord with the curve of conductor diameters and corona striking distances, *i.e.*, distances from the surface of the conductor to the critical stress, 76 kilovolts per in. zone. Such a curve is located in Fig. 7. It is of value and interest to note the almost exact agreement of these curves for diameters under *one quarter inch* (6.35 mm.). For example by the Fig. 7 curve, the spark discharge distance at minimum stress between spheres, 0.25 in. (6.35 mm.) diameter, is 0.063 in. (1.6 mm.), while the corresponding corona striking distance for a conductor, 0.25 in. (6.35 mm.) diameter, as given by the curve in Fig. 2, is 0.066 in. (1.67 mm.). Though alike in general character throughout, these curves differ totally in regard to the diameter at which the effect corresponding to part-corona makes its appearance. In corona formation about a round conductor the part-corona effect appears when the diameter has increased to about *one quarter inch* (6.35 mm.) while in spark discharges between spheres of all sizes the corresponding effect does not fully develop under a spherical diameter of *two and three-quarter inches* (7 cm.). The difference is due to the configuration of the two classes of electric fields. This is an important matter that will be taken up again in accounting for the descrepancies between corona formation results obtained by concentric cylinders in the laboratory, and by tests on the actual transmission lines.

These results no longer permit doubt to remain in regard to the fact that the electric stress required to rupture thin films is greater than the critical stress of 76 kilovolts per in., which, when uniformly distributed, is the stress required to rupture air in bulk. These results, however, do not indicate that this is due to an inherent difference in dielectric properties of air in a film and air in a bulk. They point strongly toward some dynamic action that requires a critical *minimum combination of stress and distance* through which to bring about rupture wherein any foreshortening of distance must be compensated for by an increase in stress.

At this stage of the study it became increasingly evident that the *initial corona striking* distance is a factor of real importance in the control of corona formation. It must be understood as fully as the effects of stress are now understood in order to make progress in the subject.

II. Evidence that Electric Stress is but One of Several Factors of Importance in the Production of Corona and Spark-discharge in Air or in Gases Generally

a. Recent Results and Views of Nipher. At this point a copy of the second part of Professor Francis E. Nipher's classical paper "On the Nature of the Electric Discharge".* was received. For years, by methods that have been unique for their directness and simplicity this eminent physicist has studied the nature of the electric discharge. Most physicists who have studied these phenomena employed air or other gases in a highly attenuated state. The consequence is that great difficulties are encountered when the attempt is made to apply their results to air under normal conditions.

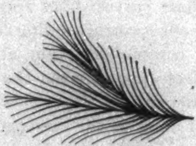

FIG. 8

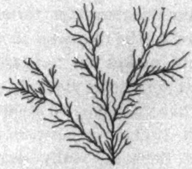

FIG. 9

Nipher's work has been done in air under ordinary normal indoor conditions. His results in the above paper show clearly the several dynamic features of the electric discharge in air. Among other important things he clearly establishes a direct relation between the electric discharge phenomena observed by him in normal air at a pressure of 29.5 in., (750 mm.) of mercury and those obtained by others at 0.04 in. (1 mm.). This paper made it possible to look to the authorities on the conduction through gases in attenuated states for knowledge in regard to corona striking distances, part-corona, discrepancies between results by concentric cylinders and parallel cylinders, meteorological factors, *et cetera.*

Nipher says that "the dissymmetry in discharge effects at the *positive* and *negative* terminals of an electric machine is now ascribed to the difference in the size of the carriers of the electric discharge," and that the evidence presented in his papers "shows that the dissymmetry is due to the fact that the negative electrons are being forced out under '*pressure*' at the negative terminal and that they are being *drawn in* at the positive terminal under conditions which may be likened to those on the exhaust side of a pump." Figs. 8 and 9 were traced from sections of Nipher's photographs of negative and positive discharges splashed from electrodes over the sensitive films of ordinary photographic plates. One sees at once in these records some cause for the above conclusion. In the *negative* splash, Fig. 8, the discharge lines are characteristic of an outward fluid flow in a vigorous dynamic state or stiff, almost unbending forms. In the corresponding *positive* splash the reverse dynamic condition holds—that of an inward gravity fluid flow in a weak state, dynamically, and easily deflected.

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*Nipher, Trans. Acad. Sci. St. Louis, Vol. XIX, p. 57, June, 1910.

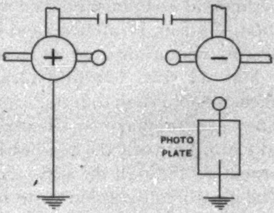

Fig. 10

The results recorded by Nipher in the photographs reproduced in Figs. 11, 12*a*, 12*b*, 13, 14*a*, 14*b*, and 14*c*, are of especial interest in connection with the corona problem of the high-tension engineer. These photographs were produced in the following manner: In each case a common photographic plate was supported, film side up, on proper insulators a few inches above the surface of a laboratory table. At the center of the plate about 4 in. (10 cm.) apart, two common pins "dry-goods" type, were mounted vertically. The pin heads were in contact with the film of the plate and the points were soldered to wires, one leading through a short air gap between metal balls to the negative terminal of the electrostatic machine, and the other to the ground; the positive terminal of the machine was also grounded. This general arrangement is shown diagramatically in Fig. 10. By trial and experience in driving the machine a great variety of discharges could be made to pass between the pin-heads through the air over the surface of the photographic plates. The discharges could be made by rushing one or two sparks across the air gap in the negative circuit and the photographic plates would record all the more important effects, since such effects are fortunately photo-active. The spark-gap length between the balls was adjustable and by turning the machine at various speeds every desired strength of discharge could be splashed through the air over the surface of the photographic plate. In this manner, then, the discharges were made that are photographically reproduced in Figs. 11, 12*a*, 12*b*, 13, 14*a*, 14*b*, and 14*c*.

This short series illustrates beautifully, practically every essential form of electric discharge that can occur through air except the ordinary *arc*, a near approach to which has occurred in Fig. 14*c*. One sees at once in these records cause for the above conclusion quoted from Nipher. The details of what happened in the discharge records of Figs. 11, 12*a*, 12*b*, and 13, as they are understood by the author, after a study of Nipher's and of other physicists work in air highly attenuated for experimental convenience, and the recent corona results of Mershon, Watson, Whitehead and others under an approach to engineering conditions, are as follows:

Figs. 11, 12*a*, 12*b*, and 13 are records of the same discharge phenomenon, each differing from the other merely in magnitude. They can properly be discussed together. The application of an e.m.f. between the pin-head electrodes results initially in the formation through the surrounding air of a field of electric stress. The glass photographic plate intensifies the field in the air next to it because of its high inductive capacity. The form of this field under the circumstances is fairly familiar to us all. In the air next to the photographic plate the initial electric field set up is very much the same as that produced in the open air between two identical parallel round conductors and mapped by the familiar Faraday tubes of force in Fig. 27. Irregular throughout as this field is, it is nevertheless practically uniform in any concentric zone near each electrode. When an e.m.f. is applied between the pin-head electrodes high enough to produce one of these splashing discharges the electric field formed through the air film under and over the edge of the pin-head, between it and the glass photographic plate is strong enough to detach some electrons from the negatively charged pin-head and eject them outward through the near-by radially uniform electric field. These initially ejected electrons strike everywhere within ultramicroscopic distances atoms or molecules of air which they "*ionize by collision*," *i.e.*, each electron that strikes an atom of air in a stress above 76 kilovolts per in. does so at sufficient

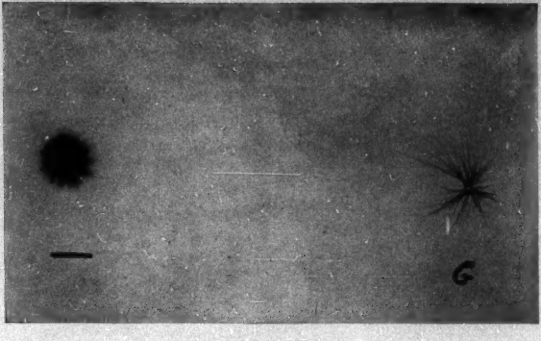

FIG. 11

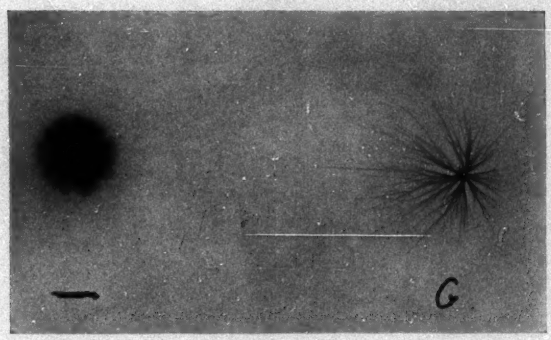

FIG. 12*a*

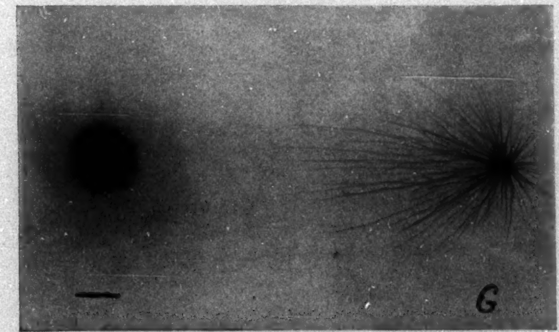

FIG. 12*b*

[Ryan]

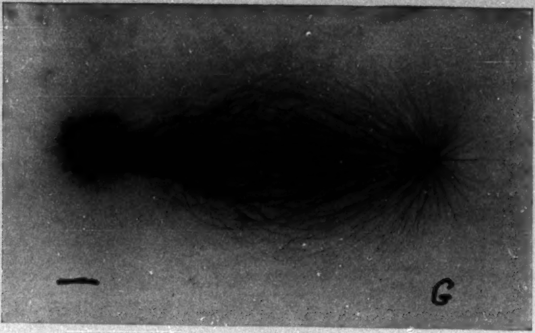

FIG. 13

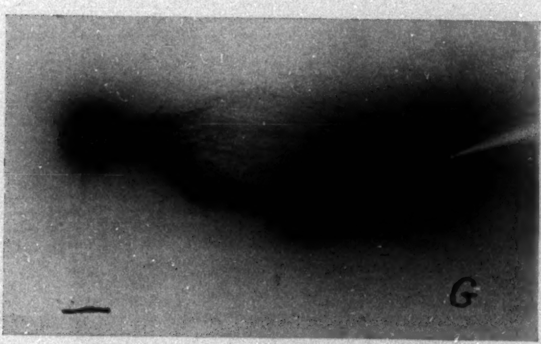

FIG. 14*a*

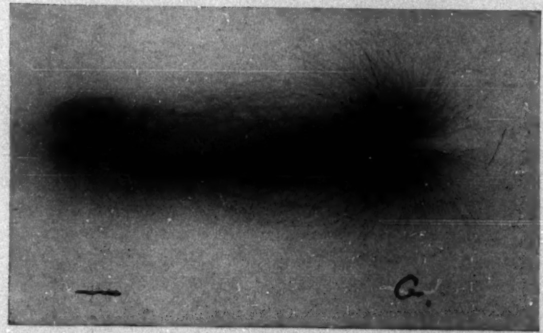

FIG. 14*b*

[Ryan]

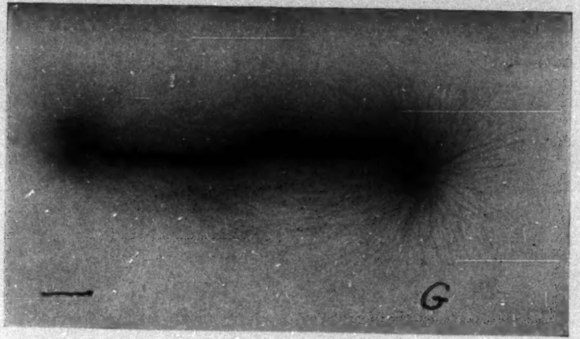

FIG. 14*c*

FIG. 29

[Ryan]

velocity to detach from such atom an electron. Two new ions are thus formed; the negative electron, and the neutral atom that lost it and which was thereby given a corresponding positive charge and became a positive ion. This new positive ion, being large, winds its way inward rather slowly to the negative electrode taking little part in the process of ionization by collision as will be seen later; the electron or negative ion, being small and in a field of ionizing stress is accelerated radially outward to collide with the next atom thus taking up its part in the spread of the ionizing process which in this fashion builds up rapidly by geometric progression. Ionization by collision is always accompanied by luminosity and is the cause of visible corona, part-corona, brush discharge, sparks and ultimately arcs.

Beyond the zone of luminous discharge at the negative pin-head the electric stress has fallen below 76 kilovolts per in. and new ions are no longer formed. By migration in the dark or " diffusion " as the physicists call it, in weaker portions of the electric field, this crop of electrons just formed continues to move toward the positively charged pin-head. Such migration is inherently an erratic process, setting up unstable forms of progress through the air, always following, turbulent fashion, the line of least resistance just as a batch of water does when splashed over an incline. The electrons in advance push aside the atoms of air and thus core out routes by which it is easier for those behind to pass. When it is remembered that these streams of electrons are the equivalent of conductors carrying currents it is easy to comprehend the manner in which they enormously alter and concentrate the normal stress of the electric field along their routes leading in erratic fashion toward the positive electrode. Such inward flow electron streams form about themselves magnetic fields that take up the role of closed elastic contractile envelopes that contract them into thin streams. The dark passage of electrons through the air is thus seen to be an erratic, turbulent process that in advanced stages cores out certain narrow channels of flow which simultaneously and completely modify the distribution of the electric field.

The electrons migrating in diffusion toward the positive electrode, are impelled everywhere by the stress of the electric field as modified by their presence; they strike everywhere atoms of air; everywhere they repel one another because they are each a negative charge of electricity. A turbulent process of this sort has its mechanical tendency to core out certain routes. Such tendency is augmented by the magnetism that must, from the start, accompany the formation of each electron-stream. Everywhere, when the *stream-forming role of the magnetic-mechanic action* is stronger than the diffusion role played by the electrostatic attraction of neutral atoms and of mutual repulsion, the electron streams will form. The magnetic-mechanic actions tend to unite the little streams into larger ones while the electrostatic forces will tend to keep them apart. In air, at a density of *one atmosphere* and with a *sufficient crop of electrons*, the magnetic-mechanic contractile role exceeds the electrostatic diffusion role, streamers form, unite and produce a solid spark. In air at 1/760 *of an atmosphere*, even with the largest crops of electrons, the magnetic-mechanic contraction forces fall below the electrostatic repulsion forces and glow discharge, only, results.

When electrons conducted by diffusion unite to form streams, the stresses of the field are enormously localized through such streams which act as conductors, with a corresponding increase in the driving force applied to the electrons in the streams. When these velocities thereby produced exceed the velocity required to ionize by collision, the banks of the streams become luminous through such process. On the banks new electrons are liberated to join the stream and a corresponding lot of positive ions of atomic size are created and migrate counter current fashion. When conduction by diffusion remains as such and fails to form streams, as it will fail to do in a sufficiently attenuated atmosphere, ionization by collision will also form when the field is strong enough to produce the ionizing velocity of the electron in its run between collisions, *i.e.*, in its free path. Glow discharge is then witnessed and there are formed diffused, opposing "*electrical winds*" of the positive and negative carriers. In beautiful experiments Nipher has demonstrated the presence of these winds.

The behaviors in the normal atmosphere above referred to are photographically recorded by Nipher as shown in Figs. 11, 12*a*, 12*b* and 13, each being a different degree of the same splashing discharge phenomenon. As stated before, one can best see all the features noted above for himself by studying these records carefully. The formation of small non-uniting streams occurs at the in-flow of the positive electrode in Fig. 11. In the slightly larger corresponding discharges of Fig. 12*a* these streams have united to some extent just before reaching their goal; their numerous sources are in the general outer region of non-luminous diffuse electron migration. Fig. 12*b* is a record made by a slightly larger discharge. In the discharge recorded in Fig. 13 the magnetic-mechanic forces exceed the electrostatic forces among the outward streams *at the negative* electrode on the side facing the positive electrode. Diffusion in that region was thereby not permitted. A group of electron streams is held together at first somewhat compactly, later more loosely as they extend to the positive goal. This is the approach to the formation of a spark.

The discharge that is recorded in Fig. 14*a* is most interesting because it shows up so clearly the mechanism of a spark in the normal air. The magnetic-mechanic forces closely confined a part of the electron crop on the side of the negative electrode immediately opposite the positive electrode, and caused such electrons to core an irregular route through the air extending somewhat over half the distance between the electrodes to a point where the forces of repulsion gained the ascendency and the spark broke, discharging its ions in diffusion toward the positive goal. The velocities remained great enough to produce luminosity. It is of great interest to note the shadow in this luminous electric wind that was cast by the positive pin and pin head in line with the discharge from the muzzle of the spark. Nipher recorded hundreds of these discharges that included sparks in all stages. He says that in every case the spark never completely extended to the positive electrode. Upon occasion sparks were recorded that extended but a fraction of an inch, *i.e.*, ¼ in. (6.35 mm.) more or less, from the negative electrode then broke into diffusion to complete the discharge over the rest of the distance to the positive electrode.*

A rational relation has now been established between electric discharge phenomena in the normal atmosphere that concern the electrical engineer and the corresponding phenomena that occur in highly attenuated atmospheres that have been studied with great care by many able physicists. The engineer can, therefore, confidently look to the results obtained by these men for much assistance in the further solution of the corona problem.

b. Townsend's theory of ionization by collision and its experimental verification; accounting for the great dielectric strength of

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*An appendix to this paper reprints Nipher's resume of his papers on "The Nature of the Electric Discharge" published in Science, N. S., Vol. XXXII, p. 608, Oct. 1910.

*thin envelopes of air covering conductors and the details of corona formation.**

Townsend, after a thorough study of the whole range of phenomena produced by the conductivity of gases formulated and successfully verified the following theory of *ionization by collision* to account for a large and important class of these phenomena. For the present purpose this theory will be best understood by the consideration of a particular example:

Two parallel plane-faced electrodes are mounted with an atmosphere between them sufficiently attenuated to permit a convenient experimental study of these matters. By any suitable means, *viz.*, ultra-violet light, condensed radium or thorium emanation *et cetera*, *electrons* are liberated from the inner surface of the negative electrode at a definite rate, *i.e.*, a definite number of electrons liberated per square centimeter per second. A uniform electric field can be established between the plate electrodes and varied from zero to any desired maximum by connecting to the electrodes a source of correspondingly variable e.m.f. The parallel plate electrodes are so arranged that their distances apart may be adjusted accurately through any desired range. A proper form of galvanometer is connected in series with the e.m.f. circuit leading to the electrodes so that the current carried by *ions* through the column of air between the plates may be correctly observed. The negative ions are the electrons, *i. e.*, definite negative charges of electricity attached or unattached to neutral atoms dependent upon circumstances of a turbulent character and the positive ions are neutral atoms having lost each one or more electrons—generally only one. The section of the air column between the plates is confined by suitable solid dielectric walls so that its section is equal to the face of either electrode.

With electrons being liberated at a certain rate from the face of the negative electrode, as the field between the plates is increased from zero, the electrons are made to migrate toward the positive electrode and a corresponding current is indicated by the galvanometer. For a certain extent the current increases with the increase in the electric field. A strength of field is soon attained, however, that is sufficient to permit no electrons to go astray and to make them all migrate to the positive electrode. Further increase in the electric field produces for a time no corresponding increase in the electric current passing between the plates; this relation continues until the electric field has been increased to the amount sufficient to accelerate the electrons to ionizing velocity while being driven through the intra-atomic distances in the attenuated atmosphere. After that, further increase in the electric field is accompanied by a rapid increase in the current indicated by the galvanometer as flowing between the plates and the discharge which, throughout has been continuous, is now accompanied by luminosity. The last is the corona stage. These relations of the current to the electric field are given by the curve drawn in Fig. 15*a*. This general statement of the facts has been necessary in order to appreciate Townsend's theory of ionization by collision and its verification.

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*The Theory of Ionization by Collision by J. S. Townsend. Trans. Int. Elec'l Congress. I. p. 106. St. Louis, 1904.

At the beginning of the corona forming stage, the strength of the field has become sufficient to accelerate the electrons in their free paths among the atoms of the air or other gases to the velocity that produces new ions when they collide with atoms in their paths. At each collision, as stated above in discussing the Nipher records, two new ions are formed; one, *negative*, *i.e.*, the newly detached electron, and the other *positive*, *i.e.*, the neutral atom that lost such electron by the collision. Under the action of the electric field these new ions begin their migration toward their respective electrodes of opposite polarity; in so doing each will collide with other atoms and will produce correspondingly at every such collision a new pair of ions when the free path traversed has been sufficient to gain ionizing velocity. Often an electron and a positive ion meet at a relative velocity low enough to permit recombination when a pair of ions is lost in the formation of a neutral atom.

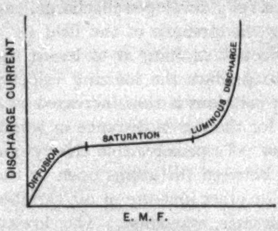

FIG. 15*a*

Since the mass of the positive ion is far greater than that of the negative ion, the electron, and since the driving forces applied by the field are alike in each case it follows that a positive ion will attain ionizing velocity only when accident gives it a free path between the atoms that is sufficient, and which in any event must be much above the free path required by the electron to produce new ions. The number of ionizing collisions made by a positive ion in migrating a unit distance will, therefore, be far less than the number of such collisions formed by an electron migrating through the same gas, field and distance. In all other ways the positive ions take part in the phenomena of ionization by collision as do the electrons.

It follows that the increase of ions by collision must occur in geometrical proportion with the distance through which the action extends. In any given case, therefore, there must always be a limiting distance at which this increase approaches infinity, *i.e.*, a distance between the electrodes in which all of the atoms are ionized, resulting in the formation of a *spark or arc*. This is the *upper limit* at which the theory of Townsend ceases to apply; the *lower limit* began at departure from the saturation current caused by the production of additional ions by collision. See Fig. 15*a*. If the striking distance between the electrodes is shortened the same result, *i.e.*, a fully developed discharge, can only be produced by increasing the strength of the field by a compensating amount. The effect of so doing is to lessen the interatomic distance required to produce the ionizing velocity of the electrons: The number of collisions is thus increased to a degree sufficient to compensate for the loss in distance in which to bring about general ionization. To perceive this clearly one must remember that the paths between the atoms open to the free movement of the electrons or other ions are of all variable lengths, from zero to some *average maximum*. The lowest electric field or electric stress at which ionization is possible is that which accelerates the electron to the ionizing velocity when traversing these longest free paths; the great majority of other free paths are too short to effect sufficient acceleration. With increase of the electric field shorter paths become effective so that increase in field strength or electric stress makes available shorter free paths, increases intensity of ionization and lessens the minimum corona or spark-striking distance. The greatest limiting distance within which a spark can not form except with increased field occurs when the electric field or electric stress is at the critical value below which all ionization must cease because the velocities imparted to the electrons between collisions are not sufficient to detach electrons from neutral atoms.

This then is the underlying cause for the existence of *the limiting corona striking distances* charted in Fig. 2 or for those effects that lead one earlier to assume the existence at the surface of the conductor of a *thin zone of air having remarkably great dielectric strength.*

From such theoretical considerations Townsend derived the following expression for the relation between conductivity and distance through a gas wherein the electric stress and mechanical pressure of the gas, the initial ions and the rate of ionization by collision in excess of recombination are all known and fixed at possible values or values convenient for experimental purposes:

$$n = \frac{n_0 (\chi - \beta)\, \epsilon^{(\chi - \beta)d}}{\chi - \beta\, \epsilon^{(\chi - \beta)d}}$$

Wherein

n_0 = the number of negative ions starting from a small surface of the negative plate electrode.

n = the number of ions passing through the corresponding section of the gas between the parallel plain conducting electrodes; this number is proportional to the current set up.

β = the number of new ions produced per centimeter in passage of a positive ion through the gas to the negative electrode.

χ = the same corresponding value for electrons or negative ions.

d = the distance between the plates in centimeters.

ϵ $\doteq$ logarithmic base.

Townsend showed that sparking must ensue when the denominator of the fraction in this expression vanishes for then the number of ions migrating per second from conductor to conductor becomes infinite. As a matter of fact the value of n can not actually become infinite; it is limited to the number of actual migrating ions when most of the atoms or molecules of the gas have become ionized. However, since such number is nevertheless very great the distance d' for such very great number of n and d for an infinite number of the same is so slight due to the nature of this expression that it is not necessary to distinguish practically between the two.

Placing

$$\chi - \beta\, \epsilon^{(\chi - \beta)d} = 0$$

the value of d for which n becomes infinite is, therefore,

$$d = \frac{\log \chi - \log \beta}{\chi - \beta}$$

This distance *d* is therefore the minimum through which a spark or corona can be struck by the given electric stress. To strike a spark or corona through a shorter distance a higher electric stress must be applied that will increase the values of χ and β and, therefore, diminish *d*.

Townsend made careful experiments to test the integrity of this theory. In one experiment the values of n_0, β, χ, *pressure* and *stress* were as follows:

n_0 = 1 negative ion per definite small portion of negative electrode surface produced by impact of ultra-violet light.

β = 0.0141 new ions produced per centimeter travel of each positive ion.

χ = 5.25 new ions per centimeter correspondingly produced by each negative ion; the new ions thus produced being precisely similar to those produced by the positive ions, except as stated above.

Kind of gas, *air*; pressure, *one millimeter of mercury*; above-critical electric stress, 350 *volts per cm.* applied between parallel plate electrodes at various observed distances apart, resulting in the establishment of an observed conduction or *n* ions per given small cross section of gas column corresponding to the small surface of the negative plate electrode whence originated by impact of ultra violet light, *one* electron or negative ion per second. The currents corresponding to *n*, in arbitrary units of experimental convenience and to the distances that separated the plate electrodes as observed in experiments and correspondingly calculated from the above theory by Townsend are tabulated in the following table:

TOWNSEND'S EXPERIMENTS WITH AIR AT ONE MILLIMETER PRESSURE AND A CONTINUOUS ELECTRIC STRESS OF 350 VOLTS PER CENTIMETER.

d in centimeters	0	0.2	0.4	0.6	0.8	1.0	1.1
Current determined experimentally		2.86	8.27	24.2	81	273	2250
Current calculated by above formula for *n*	1	2.87	8.3	24.6	80	380	2150

The results by experiment have been charted in Fig. 15*b*. They speak for themselves and constitute a remarkable confirmation of the theory of ionization by collision.

c. (1) *Application of the theory of ionization by collision under normal atmospheric conditions.* (2) *Density of air and gas and* *form of electrodes as factors controlling and limiting ionization by collision. (Includes limits due to stresses sufficient to detach free electrons from the metal electrodes, critical sharpness of needle points and corona quantity in relation to rupturing gradients.)*

Curve *I*, Fig. 6 of the Baille-Paschen-Schuster results obtained long ago with no knowledge of electrons and gas ions locates the corona striking distances at critical electric stress in the normal atmosphere at about 0.76 cm. or 0.3 in., as against the above value of 1.1 cm. in air at a pressure of one millimeter of mercury. The corresponding critical stress was found to be 31.5 kilovolts per cm. or 80 kilovolts per in., a little higher than the value generally accepted by physicists, *viz.*, 30 kilovolts per cm., or 76 kilovolts per in. From this it follows that the minimum striking distance at critical stress changes but little for wide changes in pressure. Townsend's experiments make it 1.1 cm. at 1 mm., (0.434 in. at 0.0394 in.) and the Baille-Paschen-Schuster results make it 0.76 cm. at 750 mm. (0.3 in. at 29.5 in.). These results were obtained by the use of uniform fields to produce discharges between parallel plane plate electrodes.

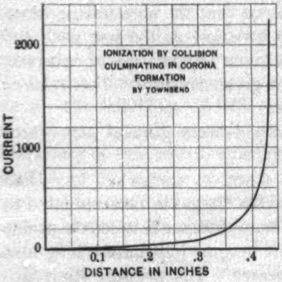

FIG. 15*b*

The same slow variation of critical striking distances between concentric cylinders at a given air pressure and critical stress made a great change in pressure at which the striking distance again became critical at critical stress.

Before going further in this use of the Baille-Paschen-Schuster results it may be well to note that at the time these observations were made as nothing was known of electrons, no radioactivity of the surface of the negative electrode was produced by ultraviolet light or other agency that would cause an initial source of electrons as was done by Townsend in his theory verification experiments. These results are on a parity with those of Townsend nevertheless, because they were obtained in the normal air, which under all ordinary circumstances contains radioactive material sufficient to ionize it somewhat. The necessary initial crop of electrons to be liberated at the cathode, is provided by the impact of the incoming positive ions. Ionization by impact will be taken up later. Electrons thus liberated at the cathode are expelled from its surface and thereby made to begin the process of ionization by collision that culminates, when the field is sufficient, in the production of corona or spark discharge. The origin and importance in the corona problem of this universal radioactivity in the atmosphere will also be considered later.

From Townsend's theory as verified, it follows that in uniform electric fields between plane-faced parallel electrodes the minimum stress required to produce an electric discharge, *i.e.*, the critical stress, must vary directly as the pressure of the air or other gas. The critical stress is the one that can accelerate the electron in the average maximum free path to ionizing velocity. Such free path must vary inversely as the density of the gas, requiring in consequence that the accelerating force, *i.e.*, the electric field must vary inversely as the free path and directly as the gas pressure at a given temperature or inversely as the absolute temperature at a given pressure. *This relation holds between the following limits*:

For uniform electric field-stresses between parallel plane-faced electrodes.

The law holds for pressure down to somewhat less than 1 mm. (0.0394 in.) of mercury whereat the gas is too attenuated to maintain a definite average maximum distance between the atoms or molecules; the long free paths become indefinitely long and luminous discharge or corona ceases. The pressure limit upwards extends indefinitely. The relation holds correspondingly for electric stress downward—and upward likewise, until, because of the great density of the gas, the stress is great enough to produce a crop of electrons at the electrodes without being sufficient to increase their number by collision-ionization. This is in one of the wholly unexplored divisions of electrical knowledge. However, many things point to about 2300 kilovolts per in. (900 kilovolts per cm.) as the stress at which the electric discharge will be produced by ions torn from the metal electrodes largely regardless of the density of the air or other gas. This behavior will be considered further on.

For divergent electric field and stress between non-planar electrodes:

Between equal parallel cylinders and between spheres the critical striking distances are dependent upon certain factors that are controlled ultimately by the curvature of these electrodes. This class of critical striking distances have been referred to earlier and are charted in Figs. 2 and 7. Critical striking distances for points, *i.e.*, electrodes having very small faces but of definite radii of curvature, have not been determined. The determinations are difficult and in the corona problem not of much importance. With pointed electrodes, however, two items of especial collateral importance in the corona problem have been brought out experimentally; and they are related to these critical distance-stress limits:

1. Fisher found that there exists a critical degree of sharpness for needle electrodes whereat the sparking voltage *for a given gap is minimum* being increased when this sharpness of the needle is either increased or decreased.* He found, for example, that with the voltage fixed at 6.2 kilovolts, (effective sine-wave) the 0.0015-in. (0.038 mm.) diameter fine needle point gave the longest sparking distance amounting to 0.422 in. (10.67 mm.) and with the voltage at 10 kilovolts (effective sine-wave), the 0.0017-in. (0.043 mm.) fine needle point gave the longest sparking distance amounting to 0.646 in. (16.4 mm.). The cause of this critical sharpness of needles used for sparking with a given voltage through a certain distance was found recently by the following method *to be due to the amount of the corona formed at the electrodes in relation to the sparking distance and voltage*:

The classical series of observations of Steinmetz was studied to secure data relating to electric discharge through the normal air using alternating high voltages and electrodes of opposing pairs of brass spheres of various diameters.†

It was noted that as long as the spheres of whatever size were so near together that the electric field between them was fairly uniform, the discharges were set up at about the normal critical stress of 76 kilovolts per in., produced of course by the maximum of the voltage waves. As the gaps were lengthened and the electric stress between the spheres became divergent the rupturing gradient, *i.e.*, kilovolts per inch between the spheres would drop rapidly to some low value, 10 to 4 kilovolts per in., (3.9 to 1.6 kilovolts per cm.), dependent upon the diameter of the spheres, being lowest for the largest spheres, and that it stayed at that value as the distance between the spheres was further increased as long as the balls were evidently not entirely enveloped in corona. Related phenomena of this character were then studied widely through the literature, including Fisher's careful observations on the electric discharge between needle points above referred to, the recent observations of Moody and Faccioli* on the voltage required to rupture the air between a round conductor mounted parallel to and at a distance from a metal plate as electrodes; including also unpublished commercial tests of high-tension suspension type, six to eight unit insulators, and accidents that produce discharges of great magnitude in the power houses and substations connected to high-tension networks.

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*H. W. Fisher, Spark Distances Corresponding to Different Voltages, Trans. Int. Elec'l Congress, Vol. II, p. 294, St. Louis, 1904.

†Steinmetz, Dielectric Strength of Air, TRANSACTIONS A. I. E. E., Vol. XV, p. 281, 1898.

This study in the light of our present day knowledge of such matters developed the following understanding as to the causes that effect the breaking down of the normal air in bulk by electric stresses that are so much below the critical stress. These bulk stresses range from 10 kilovolts per in. (3.9 kilovolts per cm.) for long gaps between needles, to 4 kilovolts per in. (1.6 kilovolts per cm.) or less between large spherical electrodes. The understanding of the matter is perhaps best presented by considering first the particular case of sparking between large spherical electrodes: As the gap between the spheres is lengthened, sooner or later, dependent upon the diameter of the spheres, the field becomes divergent. When the electric field has become decidedly divergent and the voltage required to discharge between the spheres exceeds that which is required to establish a critical stress in the envelopes of air covering the spheres to a critical depth, corona will be formed. It will appear first over limited portions of the opposing surfaces of the spheres. In this state at the negative sphere electrons are liberated by impact at its surface of incoming positive ions,—the first of these positive ions were of natural or "antecedent" origin. Ionization by collision follows and a crop of electrons results that is great enough to cause the magnetic-mechanic contractile forces to form an *electron core* against the diffusion forces of mutual repulsion, the attraction of neutral atoms and the counter electric winds of incoming positive ions. Such a core is the equivalent of a current in a conductor. The size of this core and its density of driven electrons are measures of the equivalent current and the conductivity of the equivalent conductor. If the corona formation at the negative electrodes is sufficiently great, the core will have so high a conductivity that there will be voltage enough between the spheres to drive it clear across the air gap thus producing a discharge or arc. Now the greater the diameter of the spheres, the greater will be the area over which the corona will be formed and the greater the supply of electrons in stock, therefore, with which to drive the electron core or spark from the negative to positive sphere, the higher, then, will be the conductivity of the core and the lower the corresponding voltage gradient. It is a quantitative result that is quite independent of the figure and strength of the intervening field-stress which in many portions is less than one per cent of the critical stress. No evidence could be found that the intervening strength and figure of the electric field is more than a small factor among those that determine the voltage gradient required to rupture the normal atmosphere in bulk.

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*Moody and Faccioli, Corona Phenomena in Air and Oil. TRANSACTIONS A. I. E. E., Vol. XXVIII, II, p. 769, 1909.

To assist the judgment which is ones chief resource in a study of this sort, the available data were charted in the order determined by rupturing gradients. This chart is reproduced in Fig. 16.

Returning now to Fisher's critical sharpness of needles: From a very finely tapered and pointed needle, corona is produced more easily but in smaller amounts at given voltages and spark gaps, than from the points of needles that are not so finely tapered and pointed. Thus it is seen that changing the sharpness of the needles affects oppositely the two most important factors that bring about the electric discharge through air or any gas, *viz.*:

(1) *Corona starting facility, dependent directly upon voltage* and (2) *rupturing facility, dependent directly upon corona quantity.*

An increase in the sharpness of the needle electrodes raises the former facility and lowers the latter, and *vice versa.* Thus at a given voltage there must always be some compromise degree of needle sharpness that will cause the discharge at such voltage to cross the longest gap—a discovery made experimentally by Fisher nearly ten years ago. With this understanding of the factors that control the (needle point gap) to (sparking voltage) relation the peculiarities of our standard A.I.E.E. spark gap voltage curve are easily comprehended as inherent and therefore necessary. The more or less definite degree of "sharps No.

6 " bluntness of point, end taper, main taper, straight shank and mounting all take their part in changing the supply corona and therefore of electrons as the gap lengthens and the discharge voltage increases.

The other item referred to above related to the critical distance-stress limits that is of interest in the corona problem may now be considered.

2. Some years ago experimental studies were made of the dielectric strengths of compressed air and carbon dioxide by the needle point spark-gap method.* A little later Mr. E. A. Ekern as a graduate student continued the experimental study along the same lines, with greatly improved facilities.†

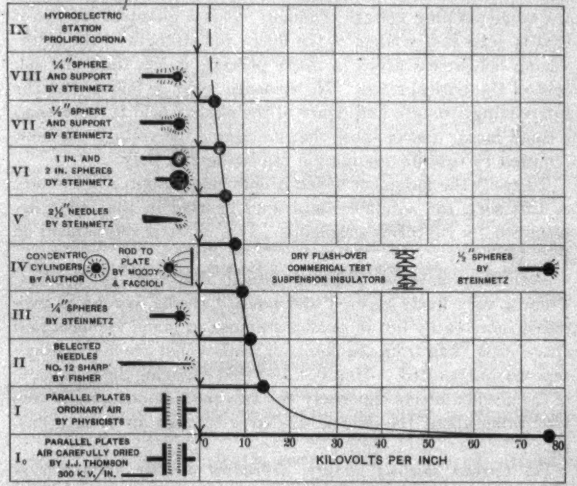

FIG. 16

In advance of these experiments it was expected that the dielectric strength of air and other gases increased directly

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*Conductivity of the Atmosphere by H. J. Ryan. *Sibley Journal of Engineering*, Vol. 18, p. 267, 1904; amplified in lecture reported in *The Electric Journal*, Vol. II, p. 429, 1905.

†" Conditions which Influence Spark-potential Values," by E. A. Ekern. *Sibley Journal of Eng.*, Vol. 18, p. 391, 1904.

as the density without limit under the approach to liquefaction. The experiments determined, however, that quite independently of the actual density of the gas the discharges would always pass between the needle points at a voltage that would be approximately *ten times* the voltage required correspondingly to produce the discharge through the gas at normal atmospheric pressure. For the most part needle points were used as electrodes. The sharpness of the needle points was varied; the electrodes were changed altogether from needles to thin rods with round or conical ends and to small spheres; in each instance the discharge distances were varied. In all cases fundamentally the results were always much the same. As the density of the gas was increased at ordinary temperatures by increasing the pressure and with the conditions fixed as to length of gap, kind and condition of electrodes, the sparking voltage would increase uniformly until it became about 10 times the voltage required to produce a spark discharge at a pressure of one atmosphere. At this stage a great change in these relations would always occur. A set of results obtained by observations made with *air* at pressures varying from 1 to 100 atmospheres or 15 to 1500 lb. per sq. in. (1.05 to 105 kg. per sq. cm.) using needle points, sharps No. 6, at three different gaps are reproduced in Fig. 17*a* from the little paper by Ekern referred to above. The results of another set of observations in this class are charted in Fig. 18 reproduced from the lecture just referred to. The electrodes used in making this set were of aluminum wire, diam., 0.09375 in. (2.38 mm.), "points" spherical; gap 0.096 in. (2.43 mm.). The gas was *carbon dioxide* and the pressure was carried through from one atmosphere to 700 lb. per sq. in.

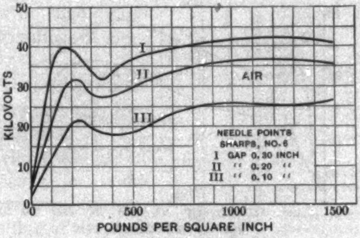

FIG. 17*a*

(49.2 kg. per sq. cm.). It was the last and best set of observations made in this class. Care was taken to eliminate disturbances introduced by the insulating supports of the electrodes, the walls of the container, *et cetera*. These results are fundamentally typical of all others obtained throughout the entire investigation.

At the time, no satisfactory explanation of the matter could be found. Now, however, the cause for the electrical failure of the gas at any density that requires for rupture about ten times the voltage that must correspondingly be applied to rupture at one atmosphere is understood to be as follows:

The conductivity of metals is due to the presence among their atoms of a certain stock of free electrons. In the metals the atoms and free electrons are very close to one another. The electrostatic attractions between the atoms and the free electrons are very great and do not allow the latter to leave the surface of the metal.* When the stress delivered from the metal electrode surface to the adjacent zone of gas is great enough some of the free electrons in the metal will be detached from the electrode and will migrate through the gas to the anode. From principles of action brought out above when this source of electrons becomes sufficient the magnetic-mechanic forces will retain them in a core that will develop a spark-discharge regardless of the stress required to ionize by collision at any particular density of the gas that may happen to be employed for the experiment. Doubtless the actual density of the gas is on some accounts, a factor

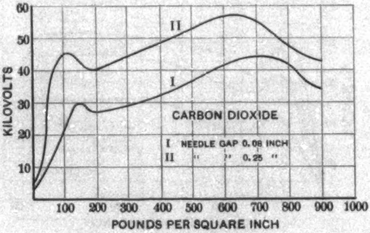

FIG. 17*b*

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*The behavior of the discharge when the plate electrodes are very close together observed by Erhart and discussed by J. J. Thomson in "Conductivity of Electricity Through Gases." First edition, p. 386.

assisting, and on other accounts opposing this process and would, if thoroughly studied, completely account for the particular form of sparking voltage-pressure characteristic obtained for a particular form of electrodes. Such study should account for the drop in gradient that follows the first stop of its increase and of its subsequent recovery. These forms in the upper ranges vary widely as the shapes of the electrodes and the gases are changed. Throughout, for the most part, at *approximately ten times the normal sparking voltage*, the density of the gas ceases to be a factor, *i.e.*, ionization by collision or corona controlled by the gas density ceases to be a factor because a new source of electrons has developed, *viz.*, the liberation of those within the metal electrode. Once formed, electrons and positive ions migrate with great facility through gases at high densities under all values of electric stress.

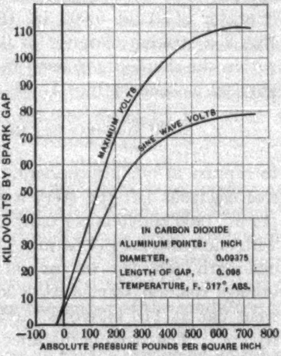

FIG. 18

The factors that bring about the detachment of the free electrons that exist in the metal of the electrodes are of great importance in some aspects of the corona problem. An understanding of the matter from a single view is not likely to be reliable unless it can be checked in various other and as far as possible independent situations. The conductors themselves as a source of ionization have been given almost no direct attention. The only data available in relation hereto have been obtained incidentally without conscious motive through efforts directed for other purposes. Erhart in the work just referred to mounted polished steel spheres at minute adjustable distances in air at various pressures from 0.02 to 3 atmospheres and observed the continuous e.m.f. required to spark between them. After the distances were so small that ionization by collision was no longer possible a discharge could always be produced when the air pressure was one atmosphere and when the stress was about

2,500 kilovolts per in. (1000 kilovolts per cm.)

The shortest distance and the lowest e.m.f. used were 0.000011 in. (0.00027 mm.) and 28 volts. In the one preceding this case there is no way of knowing with any reasonable degree of exactness the value of the stress at which the free electrons in the needle points were detached principally on account of the great disturbance of the field by the presence of a few native ions. An approximation may be made as follows: The discharge or corona striking distances for small spheres were determined from the Baille-Paschen-Schuster results, Figs. 6 and 7, to be about the same as those found for small round conductors given in Fig. 2.

From Fisher's results it was evident that the diameter of the sharps No. 6 needles used to obtain the Fig. 17*a* results had a diameter of about 0.002 in. (0.05 mm.), requiring as seen in Fig. 2 a striking distance of 0.02 in. (0.5 mm.) which is well within the shortest gap used in that set and requiring a *surface gradient* as seen in Fig. 1, of

2300 kilovolts per in. (90 kilovolts per cm.)

to rupture at one atmosphere. This makes the stress at which free electrons left the steel *needle* points in *air* 2300 kilovolts per in., (900 kilovolts per cm.). Using the later results obtained with one-tenth inch (2.54 mm.) aluminum wire, spherical points, one-tenth-inch gap in carbon dioxide, the pressure-sparking voltage relation started at 8 kilovolts at one atmosphere and went flat at 110 kilovolts, and 700 lb. per sq. in (42.2 kg. per sq. cm.). The striking distance is 0.06 in. (1.5 mm.), again well inside the length of the gap, the initial rupturing surface stress at one atmosphere is 160 kilovolts per in. (63 kilovolts per cm.) and the ratio of initial and final voltages is 13.7, making the surface stress at which the free electrons left the *aluminum wire hemispherical electrodes in carbon dioxide* 160 x 13.7 =

2200 kilovolts per in. (862 kilovolts per cm.)

These three cases occupy widely different situations and the results are in close agreement considering the circumstances. It appears a reasonable conclusion therefore that when the electric stress about a metal conductor in a gas exceeds 2000 kilovolts per in. (800 kilovolts per cm.) or therabouts, that the free electrons of the metal cathode will escape profusely into the gas and form a heavy discharge between the electrodes.

d. Stress from metallic electrode surfaces to dry high-tension insulating oil required to ionize and, therefore, to approach rupture by detaching free electrons from the metals of the electrodes.

It is of much collateral interest to know at what corresponding surface stress the electrons that are free within the metal electrodes will escape when such electrodes are immersed in a highly fluid dielectric such as high-tension insulating oil that has been carefully treated so as to remove all free ions as far as possible, *i.e.*, treated so as to raise its specific resistance under the stress of a continuous e.m.f. to the highest attainable limit. The intermolecular spaces of such oil are very much less than in gases except when the latter are near the point of liquefaction. The molecules of the oil would be in the aggregate much nearer the metallic atoms of the electrodes than in the case of a gas-immersed electrode. The free electrons in the metal would be attracted by the molecules of the oil as well as the atoms of the metal in greater degree than in the case of gas immersion. It seems reasonable to expect, therefore, that in oil at its very best the electrons should be drawn from the metal by the oil at a decidedly lower stress than the corresponding stress when gas is used. This view is supported by the fact that when gas is used the electron extracting stress drops considerably as the point of liquefaction is approached. Moody and Faccioli* experimentally studied the formation of corona about conductors immersed in high-tension insulating oil. The electrodes were wires, 15 in. (38 cm.) long and metal plates, mounted parallel, at a distance of 6.5 in. (16.5 cm.) from the center of the conductor to the face of the opposing plate. The diameters of the wires and the corresponding effective sine-wave corona producing voltages are given below:

Diameter		Kilovolts
Milimeter	Inch	
0.50	0.02	50
1.00	0.04	60
1.27	0.05	80
3.05	0.125	100

The corona formed about each of the first three small wires was maintained continuous, producing about them a highly ionized gaseous envelope. In regard to corona formation about the last wire, considerably larger than the others, it was said "the brush will appear at about 100,000 volts, and if we raise the potential the brush will appear and disappear again irregularly; that is we have an intermittent luminous phenomenon which represents more of an interrupted arc than the regular corona." * * * * "The large wires under oil, as we have said, give very unsteady and, therefore, unsatisfactory results."

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*Moody and Faccioli, " Corona Phenomena in Air and Oil." TRANSACTIONS A. I. E. E., XXVIII, p. 769, 1909.

Before giving the electrode surface stresses produced by the voltages at which these coronas under oil were produced it is necessary to understand the basis for comparing stresses that must be employed when changing dielectrics. All dielectric stress must be understood in terms of the strain it produces, *i.e.*, the displacement quantity or time-integral of charging current, *viz.*, the coulombs per unit-cube. In no other way can the terminal effects due to the substitution of dielectrics be properly compared. This system of designating strain as a result of stress is not as yet generally understood hence the necessity of stating resulting strain in terms of stress in air, the standard dielectric, that would produce the same strain in coulombs of charging current per unit air-cube. The specific inductive capacity of oil is about twice that of air. The strain in oil produced by a given electric stress is, therefore, about twice the corresponding strain produced by the same strain in air. To use the air as a standard for gauging electric strains it is necessary to multiply stress in other media expressed in voltage gradients, kilovolts per in., by their specific inductive capacities.

The following electrode surface stresses required to produce corona under oil were calculated from the above observations of Moody and Faccioli:

Diam.	Kilovolts	Stress in oil adjacent to electrode surface	Corresponding strain using air as standard
Inch		Kilovolts per in.	Kilovolts per in.
0.02	50	987	1974
0.04	60	1040	2080
0.05	80	830	1660
0.125	100	670	1340

The first three average a strain of 1900 kilovolts per in., (750 kilovolts per cm.) in the thin gas envelope surrounding the wires. The average of the above Erhart-Ryan-Ekern electron extracting strains obtained in air was 2330 kilovolts per in. (917 kilovolts per cm.) These results are interesting though they are not those that are wanted. Ordinarily there must always be a few electrons escaping from metals immersed in oil to form ions that give rise to its so called insulation resistance because under thermal agitation some of the oil molecules must be driven close in among the metallic atoms so as to meet and capture some of the free electrons regardless of the amount of electric stress extending from the conductor into the oil. This escape of electrons into the oil is very small. When a sufficient electric stress is applied from the electrode to the oil the average maximum amplitude of the electrons swinging in an out of the surface of the conductor-cathode will be increased so as to bring them near enough to the oil molecules to be captured and prevented from returning to the conductor. This is the *critical liberating stress* that is wanted. Taking all the circumstances into account it seems reasonable to expect that such critical stress must be much below that which will be strong enough not only to liberate the electrons from the cathode but will also drive the ions thus formed in the oil away from the conductor with such violence as to resolve the oil into a luminous envelope covering the conductor with highly ionized and heated gas. With these considerations in mind the behavior of the 0.125-in. (3.05 mm.) conductor, the last in the above series, is not surprising. With this much larger diameter the stress is far less divergent, which facilitates the magnetic-mechanic electron core-forming process. Before general corona could be established one or more of these cores or brushes appeared at 100 kilovolts which the authors accepted as the corona starting voltage; it is, however, probably much less than that which would have enveloped the 0.125-in. (3.05 mm.) conductor with a covering of corona pervaded oil gas. The corresponding *strain* is much lower than the average of the three preceding cases, *viz.*, 1300, being but little more than *one-half* of the value found for the liberation of electrons from metal to air.

If oil-immersed electrodes of much larger diameter were used the electric fields would be much less divergent and the core forming would follow promptly upon the initial start of the electron liberation process as the stress is increased. It was found that Tobey had made dry oil rupturing tests using brass spheres as electrodes having two-inch (5-cm.) diameters set for various gaps from 0.4 to 4 in. (one to 101 mm.).* The Baille-Paschen-Schuster results may be employed to obtain the constants that depend upon the figure of the electric field when spheres are used for electrodes. This saves a lot of mathematical work. In this way the stresses in the oil adjacent to the opposing faces of the spherical electrodes corresponding to the voltages that ruptured the oil were easily computed. In Fig. 19 Tobey's original voltage to distance curve has been re-drawn and the results obtained as above were used to locate in the same illustration the ***surface stress*** to ***distance***, or ***kilovolts per in.*** to ***inches*** curve. It is natural that this relation should be totally

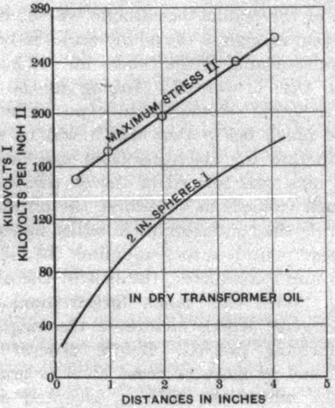

FIG. 19

rectilinear because the turbulent ionization by collision, the all important factor in electric discharge through air and gases generally, is absent or practically absent in oil. In air when electrons are liberated in corona formed only over the face of the electrodes the relation is rectilinear—a matter discussed earlier in this paper.

This right-line relation of surface stress and distance between the two-in. (5-cm.) brass spheres holds upwards from 0.4 to 4 in. (one to 101 mm.); if it also holds downwards indefinitely, as it seems reasonable to expect that it should, then the stress at which electrons are liberated from metals into dry high-tension insulating oil is 140 kilovolts per in. (55 kilovolts per cm.).* This is a most surprisingly low value—and if fully verified will form a basis upon which to account for the behavior of the oil switch; it may also have an important bearing upon the design of oil-filled insulation spaces in high-tension transformers to prevent the slow disintegration of oil and solid insulation.

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*W. H. Tobey. Dielectric Strength of Oil. PROCEEDINGS A. I. E. E., July 1910, p. 1171, Fig 6.

III. Electrons, Ions and Ionization

a. The fundamental purpose of this paper is to discuss the high-tension transmission corona problem in the light of the evidence available at the date of its preparation. The foregoing foundation was placed to support this discussion and is necessarily incomplete. In some respects it is incomplete for lack of further knowledge, while in other respects it is incomplete because it is not effective to treat too many related things at one time. For this reason certain things have heretofore been merely mentioned or consciously omitted and will now be considered more fully.

The important part that ionization plays in all phenomena that lead to the formation of corona is now clear. The corona phenomena that remain to be accounted for are of such a character as to require for their ultimate understanding a thorough knowledge of the origin, inherent qualities and characteristic behaviors of ions, *i.e.*, of the electricity carriers in gases.

Every material substance is made up of atoms or their elemental aggregations, molecules. Each kind of substance has certain distinctive characteristics because of some structural

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*Attention was not directed to these phenomena in oil until well toward the close of the preparation of the present paper. Time did not then permit a careful laboratory study to determine whether the rupturing surface stress to distance curve, *II*, Fig. 19, does or does not remain a right line locating a limiting surface stress, in this particular case, of 140 kilovolts per in. (55 kilovolts per cm.) at zero distance between the spheres. Some experiments of this sort were hurriedly performed using dry transformer oil between two-in. (5-cm.) polished steel cylinders at distances varying from 5 to 20 mils. Difficulty was encountered in an effort to obtain consistent results, apparently because of the ease with which the metallic surfaces would capture films of ionized gas at the first application of the electron-detaching stress. The results indicated, however, that the right line, Fig. 19, curve *II*, descends to the vertical axis locating a critical stress of 140 kilovolts per in. (55 kilovolts per cm.) from brass surfaces to high-tension insulating oil as stress and strain required to detach free electrons from metals.

character of its atoms. All kinds of atoms have one feature in common. Each atom holds through electrostatic attraction a certain number of relatively minute particles. The number of these particles is different for different atoms. Each particle is the ultimate and non-detachable terminus of a certain definite tube of electric force or, as some would say, it is the seat of a certain definite electric charge. The amount of this charge is 4.65×10^{-10} electrostatic units—perhaps a little larger, not exceeding 5×10^{-10} electrostatic units. In the literature of the subject this ultimate particle of matter is burdened with two names *electron*, the one apparently in more general use, and *corpuscle*, the original term used consistently by some of the best known physicists. The frame of the atom is the whole of the atomic structure less the electrons and their non-detachable electrostatic fields. The atomic frame is the common anode terminus of the electric fields or tubes that constitute an essential part of the electrons. The anode terminus of the electron field is, if not altogether detachable, at least transferable from one atomic frame to another.

A positive ion is formed when any neutral atom, molecule or atomic aggregation has, through any cause lost one or more electrons—usually but one. It thus becomes a positively charged ion. If the gas in which it is located is pervaded by an electric field it will be subjected to a corresponding force that will cause it to migrate in the general direction of the cathode or negative terminus of the field. The smallest positive ion is, therefore, a single atom that has one less than its normal quota of electrons. The largest may be any aggregation of atoms or molecules held together by the electrostatic field due to the loss from the normal stock of the aggregation of one or at the most a very few electrons.

A negative ion is any free electron, or any atom or unit atomic aggregation that has captured electrodynamically one, or at the most, a very few electrons more than the supply that constitutes the neutral atomic state. The smallest negative ion is a single electron—vastly smaller, therefore, than the smallest positive ion. The smallest positive and negative ions are alike, therefore, in the charges they carry and forces with which they are drawn through a common electric field. In sizes and masses of the smallest ions, the positive is, therefore, far greater than the negative ion. It follows that the mechanical activity of the smallest negative ion is far greater than that of the smallest positive ion.

In the open air, the natural ions present are in a comparatively quiescent state. By their electrostatic forces they have captured various molecular aggregations, generally made up *mostly, though not necessarily, of water*. These captured aggregations are retained while the dynamic activity of the ions is low. When, however, this activity is increased, by the presence of a sufficient electric field, such as is comparable with the fields set up about high-tension circuits, the forces that have captured and retained the aggregations are no longer sufficient to hold them and they are lost. Thus it occurs that all ions that take direct part in the corona formation or in the essential phenomena that precede the corona state are only those of smallest size, *viz.*, the electron and the neutral atom less an electron. This is so because all such phenomena are brought about by ions in a high state of electrodynamic activity.

The ionization of the atmosphere in the open has been and is now being studied to an enormous extent by meteorologists and physicists. The former have direct need of the most complete knowledge of the ionization of the air while the latter are particularly interested in the radioactive character of the various emanations of radium, thorium, *et cetera*, that are constantly escaping into the atmosphere from the earth. The following nomenclature has been proposed for ions of the various sorts physically that are found native in the open air:

" Let the ion formed of atom and electron be called a *nucleolus*, such an ion surrounded by molecules forming a solid or liquid mass be called a *nucleus*, and let a collection of molecules in the form of a vapor round a nucleus or nucleolus be called an *envelope*; then the three types of gaseous ions are (1) *nucleolus alone*, (2) *nucleolus and envelope, and* (3) *nucleus and envelope*. The third type merges into the visible drop of fog and rain."*

b. Sources of Ionization about High Voltage Transmission Lines.

These sources are:

1. *Radioactivity* that is entirely natural in the open air.

2. *Impact* of ions at the surfaces of conductors caused by the electric field.

3. *Collision* of ions and atoms when the field exceeds the critical ionizing strength.

As already stated the radioactivity that is always producing ions in the open air is due to the presence of emanations that are constantly escaping from the earth and subject to rapid radioactive decay. Every conductor exposed in the open collects upon its surface some of these emanations—the real essence of the "dirt" that causes the cathode conductor to start *part-corona* at abnormally low voltages. The emanations carry positive charges and are captured in abundance and retained by negatively charged conductors mounted in the open.

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*W. Sutherland, " The Ions in Gases." Phil. Mag. 18. pp. 341–371, Sept. 1909. Quoted from Science Abstracts No. 1731 p. 584, Oct. 25, 1909.

On land the radioactive emanations escape everywhere directly into the air. All underground waters absorb these emanations. Under the sea, lakes and rivers the emanations that escape from the earth are absorbed by the water. In porous rock formations, particularly of recent volcanic origin these emanations escape more plentifully. During the rising barometer air is being forced into the porous earth's crust; at this time a noticeable falling off of the ions in the air occurs due to a partial suspension thus produced of the supply of radioactive emanations. When the barometer is falling air is withdrawn from the earth and with it the accumulated emanations. At such time the ions present in the atmosphere are always observed to increase.

The emanations absorbed by the sea, lakes, *et cetera*, are liberated plentifully along the shores or elsewhere when agitated by breakers, white-caps and waterfalls.* Ions from these water sources are apt to be heavily laden with water and will behave more or less in a class by themselves.

The degree of ionization as affected by radiations arriving from cosmic space has been studied in some respects during recent total eclipses of the sun. There are effects of this character though they constitute a small factor in the corona problem.

The escaping emanations carry positive charges. The result is that the earth whence they escaped must carry a negative charge. The positive and negative ions that are formed in the air by the radioactive decay of the emanations are necessarily about equal. In addition to these are the positive ions that constitute the ionizing emanations. Such a state gives rise necessarily to a positive charge of the atmosphere relative to the earth. Near the surface of the earth there is thus produced an electrostatic field that forms a potential gradient of about 20 volts to the foot or about 70 volts per meter. In the upper regions of the atmosphere the difference between the quantities of positive and negative ions present per unit volume is greatly diminished due probably to the fact that the emanations that reach the upper atmospheres are well on the road toward complete decay; probably, to some extent, also, because of the downward forces exerted on all positive charges by the field. The consequence is that the electric field in the upper regions is greatly diminished; it is estimated by specialists to be practically zero over land of usual topography at an elevation of about 50,000 feet, (15 kilometers). Fig. 26 is reproduced from a paper of Liebenow read before the Elektrotechnische Vereins.* The curve in this illustration gives the strength of the earth's electrostatic field in relation to altitude. The vertical values designate the fields in volts per meter and the horizontal values the elevations in kilometers. The original chart was expressed in different units. The slope of this curve at any altitude is proportional to the number of positive ions present per unit volume at such altitude in excess of the corresponding number of negative ions. The actual number per cubic inch even near the earth's surface required to account for the changing gradient, *i.e.*, for the existing electrostatic field as a whole, is quite small, *viz.*, about 30. In any event the number could not be larger because of the extraordinarily small quantities in which the emanations occur. Curve II in this illustration is the integral of curve I. It shows that the potential of the earth is 164,000 volts, negative. It is found quite generally that the ionization of the air is higher on mountains. This is manifestly due to the negative charge of the earth; the mountains act like sharp projections from the surface of "*the charged conductor*" in the familiar electrostatic experiments that delighted our forefathers; they concentrate the earth's electric field which in turn concentrates the radioactive emanations thereby frequently causing a very high degree of ionization. Among high mountains the ions in the air will, therefore, vary

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*Wireless telegraphy is best conducted in an atmosphere free of ions. The ions present are driven back and forth by the electric oscillations thereby dissipating their energy. Wireless stations will not do so well by the sea, on porous volcanic earth nor at high elevations. The earth is negatively charged, which causes a concentration of the radioactive emanations and their ions over all elevations. These results in wireless telegraphy have been reported to the author by experienced men in the San Francisco Bay region.

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*C. Liebenow, "Uber tellurische Elektricitat." Presented at a meeting of the Elektrotechnische Vereins Oct. 23, 1900. Reported in the *Elektrotechnische Zeitschrift*, Nov. 15, 1900, p. 962.

greatly. The electric field, and therefore, radioactive emanations in the canyons will be smallest and on the peaks highest.

Any considerable change in the altitude of a transmission line must also constitute a corona forming factor. An extreme case would be that of a hydroelectric plant located in the Sierras at an elevation of 8,000 ft. (2438 m.) delivering its power to the San Francisco Bay region high-tension network. From the potential curve in Fig. 26 it is seen that the atmospheres at opposite ends of this line are at a potential difference of 100,000 continuous volts. At the sea level end such a line would have the average zero potential of the high-tension network. The air about the Sierra power house terminal would be at a continuous potential of 100,000 volts above that of the line. A large supply of radioactive emanations would be drawn toward and deposited upon the surface of the conductors, or held in suspension in their neighborhood. About the high altitude portion of the transmission line there would be at all times an abundant crop of native ions. The effect of this would be to increase the in-phase sub-corona diffusion current, or *convection current*, and to lower correspondingly the critical voltage at which part-corona would begin, though it would alter but little the value at which complete corona would be started.

On the other hand a short high-tension line erected on a mountain side, having small change in altitude, such as Mershon used in his high-tension atmosphere line-loss experiments at Telluride, Colo., in 1896, may escape all effects of the above class due to altitude. In fact such a high-altitude line, when located so as to be sheltered from the radioactive emanations that collect around the neighboring peaks and ridges may have a relatively higher than normal critical voltage at which *part-corona* will be started. At low barometric pressure *full-corona* will start at a corresponding lower voltage. On approach to such corona voltage the in-phase diffusion current carried by natural ions will be less, being approximately proportional to the voltage. The ability to " core up " or " brush " and thus to start part-corona depends upon the magnitude of this diffusion current; such ability will, therefore, be less. This brush or part-corona starting voltage is the *critical voltage* as defined by Mershon.*

From many laboratory experiments it is known that the part-corona voltage range, *i.e.*, the difference between the critical voltage (Mershon) and the initially complete corona voltage varies much with the density of the atmosphere. The difference is decidedly less at two-thirds of the density of the normal atmosphere such as obtains at Telluride. It follows that the topographically protected short, high-altitude, high-tension transmission line will have a Mershon critical voltage above the normal, allowance having been made for change in density of the atmosphere due to the altitude and temperature upon which full-corona voltage directly depends.

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*Mershon, " High-Voltage Measurements at Niagara." TRANSACTIONS A. I. E. E., Vol. XXVII, II, 1908, p. 886, Fig. 38.

In clear weather under average conditions there are found in the air over land about 32,000 ions of either sign per cubic inch (2000 per cubic centimeter) and over the sea about one half this number. Cloudy, sultry weather diminishes their number—the smaller ions probably being captured by slow moving water and dust aggregation amounting, if this is so, to no real diminution. The evidence in regard to the rate at which ions are created is not concordant, apparently because of experimental difficulties in the way of distinguishing single ions from their aggregations. Perhaps the most reliable determination is that of Wilson who found in air, over land, enclosed, and dust free, 500 of either sign per cubic inch per second (30 per cubic centimeter per second).* Correspondingly in the air over sea the number of ions of either sign has been found to be much smaller, *i.e.*, about one fifth of the number correspondingly found on land. A recent authoritative work states that about 100 ions of either sign are created per cubic inch per second in air over land and from 15 to 30 correspondingly over sea.† Beyond the fact already mentioned that ionization of the air is increased to *ten times*, more or less, dependent on altitude, topography, *et cetera*, on mountains due to the negative potential of the earth, little is definitely known quantitatively of these matters at high altitudes.

d. Ionization by impact; its place in corona formation, as affected by absolute voltage and frequency.

Without the prior existence of natural ions in the air corona would not be formed except at extraordinary stresses, as has already been shown. It has also been shown that ionization by collision will build up an unlimited degree of ionization from an extraordinarily small degree of native or antecedent ionization with which to begin the action. It may hardly be said that ionization by impact is absolutely necessary in corona formation; in laboratory experiments, particularly at low barometric pressures and with the aid of a strong source of antecedent ionization such as ultra-violet light, X-rays, *et cetera*, corona can be produced with practically little or no antecedent ionization. However, under practical conditions where there is no artificial antecedent ionization corona can be started at the positive electrode *only by incoming negative ions* driven at ionizing velocity due to corresponding electric stress and at the negative electrode *only by out-going negative ions*, liberated by *impact* of incoming positive ions. Under practical conditions, therefore, no corona will form on electrodes of either sign without a natural source of ionization and none will be formed at the *negative electrode* without some source of negative ionization *at its actual surface*, or very near thereto. The known sources of negative ions at the surface of the cathode conductor are *impact* of incoming positive ions, *radioactive emanations*, *i.e.*, " dirt ", captured by the cathode and near the surface, *collision* with neutral atoms of those few incoming positive ions that happen to find open a sufficiently long free path in which to attain ionizing velocity. Of these three, impact, emanation and collision, impact is of predominating importance. Emanation is ordinarily of far less importance, though when the conductors are generally covered with an active emanation, part-corona will start at a much lower voltage than the normal, *i.e.*, the Mershon critical voltage *at the cathode* will be much reduced. Collision is of doubtful extent and a small factor prior to the start of full corona.

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*C. T. R. Wilson, Sci. Abs. No. 849, 1901.

†Radioactivity and Geology, 1909 edition p. 192, by J. Joly, F. R. S.

It has been known for twenty years that the cathode when mounted in an attenuated gas and a high voltage applied to it will emit cathode rays only when the canal rays are allowed to impinge upon it.* In modern terms, it was found that the positive ions when driven against the face of the cathode by the electric field will cause it to emit electrons. Owing to the size the positive ions in a strong electric field move much more slowly among the atoms than the electrons; they rarely find free paths long enough to acquire ionizing-velocity; their movements can not be traced by resulting luminosity as is the case with the electrons.

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*Schuster, Proc. Roy, Soc. xlvii p. 557, 1890. Results employed by J. J. Thompson in " Conduction of Electricity through Gases." First Edition, p. 383 and 384.

On account of the fact that this form of ionization is an important factor in corona formation a very limited first hand study of it was made as follows: Referring to Fig. 20, a pair of concentric cylindrical electrodes were mounted under the glass bell-jar of a laboratory vacuum pump. The dimensions of these electrodes are given on the inner pair of cylinders, Fig. 5. The air was exhausted to a pressure of about 3 in. (7.6 cm.) of mercury. A limited alternating 60-cycle discharge was then established between the cylinders by applying the high-voltage through a column of tap water contained in a glass U-tube. The discharge could be conveniently observed from the top. In Fig. 20 there is a reproduction of the sketch that was made by hand while observing the discharge. The discharge would assume different appearances and positions. Examples of these are sketched in Figs. 20, 21, 22 and 23. Fig. 24, *a* and *b* are views from the top and side through a synchronous stroboscope. Fig. 25 is a top view through a revolving mirror. When using the stroboscope, an alternating arc operated from the same source as the high-tension circuit, was mounted and dimmed so that with the aid of a mirror, it and the discharge could be observed through the stroboscope together without changing the position of the observers eye. The instrument could be conveniently adjusted by hand for instantaneous observation at any desired phase as in Fig. 24*a* and 24*b* and 180 degrees remote

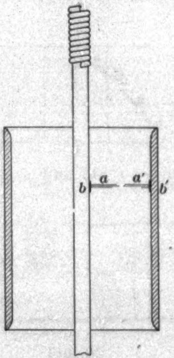

FIG. 20

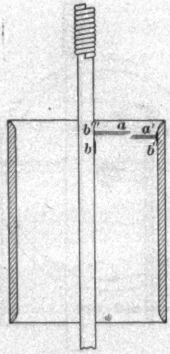

FIG. 21

therefrom when the brush *a* and the spot *b* had exchanged places and for observations at all intermediate phases. Thus with the aid of the bright positive carbon of the arc and a carefully checked knowledge of the connections the cold bright luminescent spot, *b*, was observed to be located on the surface of the *cathode* and the yellow-violet *brush* was found to extend from the *anode*.

The somewhat attenuated atmosphere at a barometric pressure of about 3 in. (7.6 cm.) of mercury affords conditions that are favorable for bunching the travel of positive as well as negative ions. The magnetic-mechanic forces play the same role of a contractile envelope for both classes of ions. Under most circumstances as already stated the negative ions are the tiny active electrons while the positive ions are never smaller than the single atom and correspondingly less active. The consequence is that conditions which readily drive the one kind into cores will drive the other into diffusion and *vice versa*. In these experiments the density of the air was so adjusted that both classes of ions were driven into cores.

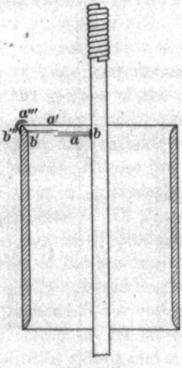

FIG. 22

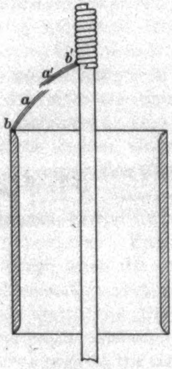

FIG. 23

With the general knowledge of these matters in mind when viewing such discharges through the revolving mirror, Fig. 25, the phenomena of the discharge are easily traced to basic facts and principles. Through the mirror the cold bright luminescent spot, *b*, on the surface of the cathode is drawn out into a band having no thickness; it is flat upon the surface of the conductor. Correspondingly the brush, *a*, attached to the anode is drawn out into a sine wave form solidly illuminated by the same yellow-violet glow. It appears like a colored trace of some sine-form alternation. The cold-bright cathode spot, *b*, is the light that is produced in the process of ***intensive ionization by impact*** of canal rays, *i.e.*, the incoming core of positive ions being driven by the field and cored mechanically by being forced into the route of least resistance and magnetically on the principle that each traveling ion has its equivalent in a tiny conductor carrying current and that like conductor-currents attract one another. The yellow-violet brush, *a*, is a luminosity that accompanies a fully matured process of ionization by the collision

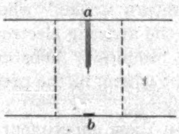

FIG. 24*a*

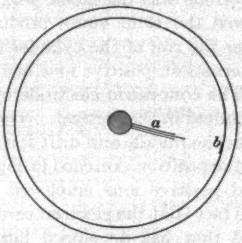

FIG. 24*b*

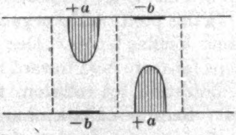

FIG. 25

of the negative ions, electrons, in this case and neutral atoms. The electrons that are detached by impact at the cathode are expelled from the cathode at ionizing stress by forming new atoms by collision as they proceed. Toward the crest of the voltage wave the process attains general ionization starting the brush just as the electrons strike the surface of the anode; at higher voltage the process culminates earlier, *i.e.*, at a shorter striking distance from the cathode and at a greater distance from the anode, producing a taller brush. In this way the brush constitutes a kind of a glow oscillograph for the top portion of the voltage wave.

Returning to the Figs. 20–23 series. These are sketches of the discharge as it appeared to the unaided eye in four typical positions. After the use of the stroboscope and the revolving mirror it is easy to understand what is going on by direct view. The discharges sketched in Fig. 20 used a common route for both positive and negative ions. The electrons travel easily between the larger positive ions. Mechanically the streams, though opposite, interfere but little; magnetically they possess a common contractile envelope that cores them together in the same space. In Fig. 21 the mechanical and electrostatic interference of the two streams has caused them to core up in part along separate routes. In Fig. 22 the same general class of causes produced an interesting result. The positive ions missed the top edge of the outer electrode through the thermal, mechanical and electrical interference and struck the cathode from the rear by the in-draught of the electric field in that region. It is further of great interest to note that on the "return stroke" when this electrode was the anode that some of the arriving electrons followed the same route producing the luminosity lines curving over the rim of the cylinder to the spot where, in the preceding alternation, positive ions had been striking.

The concentric electrode cylinders in these experiments were mounted in the vertical. The discharges would invariably strike near the middle and drift spirally upward and lodge permanently in the position sketched in Fig. 23. In this position the negative and positive ions employed the same landing spots. Due to the fact that the electron core develops far more heat toward the end that has developed luminous ionization by collision, the buoyancy of that end is the greater. Because of lack of symmetry in respect to buoyancy when the luminous portion of the electron core on the return stroke strikes the copper wire wound about the top end of the central brass cylinders it is carried slightly higher than when it strikes the top edge of the outer cylinder quite exactly as sketched in Fig. 23.

The further evidence in regard to ionization by impact is not nearly so complete as it should be. Much of it is indirect in character. Physicists have studied the phenomenon only as occurring at the cathode whence the resulting electrons are expelled in a field sufficiently strong to ionize by collision.

There is no *direct* evidence that positive ions are produced at the anode by the impact of incoming negative ions or electrons. Likewise there does not appear to be anything known of the limiting stress below which ionization by impact will not occur at the cathode. There is much indirect evidence that this class of ionization is produced abundantly only at stresses that are comparable with that required for ionization by collision. The same class of evidence indicates that at much lower stresses ionization by impact continues to occur but to a far smaller extent. The evidence shows that at the lower stresses, *i.e.*, 0.1 to 0.01 of critical collision stress, a very few of the incoming positive ions at the cathode produce negative ions by impact; most of them simply discharge and wander off as neutral atoms.

About a transmission line some ionization by impact begins at voltages that are as low as a tenth of those that produce the first traces of corona. The in-phase line charging currents observed below critical voltage by Mershon at Telluride and Niagara Falls, by Smith at Worcester and West on the Shoshone-Denver 100-kilovolt high-altitude line are carried by incoming natural ions kept alive by impact. Not all are thus kept alive and some are lost by *recombination.* The stock of natural ions about a transmission line, operated below critical voltage, is augmented by natural ionization in the air and by radioactive emanations adhering to the conductors and maintained by impact until the rate of recombination equals that of supply. With increase of voltage the effect of the field is to entrain natural ions in larger numbers; all the ions migrate faster so

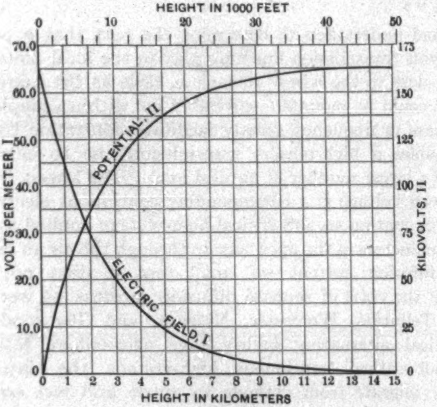

FIG. 26

that the in-phase current thus carried as found by Mershon at Niagara, increases approximately as the voltage and the corresponding loss as the square of the voltage. In any event the amount of this loss is small compared with that produced by the inphase current carried by the ions formed in a fully developed and extended corona; it is entirely comparable in magnitude with the loss caused by part-corona.

That a high-tension transmission line does capture and operate as current carriers the native ions that are formed in its neighborhood, must be true because almost no ions can be found near such a line when in operation. Houllivigne " concludes from his experiments that very close to the wires there are sensibly no ions ".*

He had undertaken to determine the part that a particular 50-kilovolt transmission line may play in the local meteorology. " Very close to the wires " means as close as the sampling apparatus could be mounted—probably not within a couple of feet.

Increase in frequency greatly facilitates ionization by impact and enables a high-tension transmission line to entrain and operate a larger number of natural ions. The lowest frequency at a given voltage is a corresponding continuous electromotive force. A continuous sub-critical high voltage applied to parallel clean conductors in the open sets up through the air an extremely small diffusion current—so small that it does not appear to be in the class of inphase diffusion currents as were found in the Telluride, Worcester, Niagara, and Glenwood-Denver sub-critical alternating high-voltage atmosphere loss tests.† With sub-critical continuous high-voltage the native ions actually migrate from cathode to anode and *vice versa*. All portions of the field traversed are very weak except those quite near the conductors. The velocity of the ions is, therefore, very slow and the opportunity for recombination correspondingly great. The result is that an early limit is set for the total stock of entrained ions that are shuttled to and fro by the high-voltage field. An abundant recombination disposes of the additions from natural sources.

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*L. Houllivigne, " Ionization of Air by High-tension Overhead Wires." Comtes Rendus, 148 pp. 1668–1670, June 21, 1909. Quoted from Sci. Abs. No. 1430 p. 480, 1909.

† Mershon: TRANSACTIONS A. I. E. E., Vol. XV, p. 545.

Mershon: TRANSACTIONS A. I. E. E., Vol. XXVII, pp.864–881.

Worcester Poly. Inst. E. E. Dept., Thesis under direction of Harold B. Smith, 1901.

West: Tests of Glenwood-Dillon-Denver-Boulder 100-kilovolt 181-mile Transmission Line, July and Nov. 1909. (See current A.I.E.E. TRANSACTIONS, p. 77.)

With sub-critical alternating voltages the ions do not have time to migrate from one conductor to another. About the cathode conductor during a positive high-voltage alternation the negative ions are expelled through the tubes of the electrostatic field, Fig. 27, *a portion of the way* to the anode conductor, and the positive ions are correspondingly drawn in a certain distance; during the next alternation the field is reversed and the ions make a corresponding return journey. Through a combination of factors the ions will make a somewhat greater distance when travelling inward through a contracting electric tube of force than correspondingly outward through an expanding tube. The consequence is sooner or later that all ions that are repelled at one alternation will return in the first half of the next to strike the conductor surface reverse sign and retreat under expulsion before the close of the alternation and the beginning of the next.

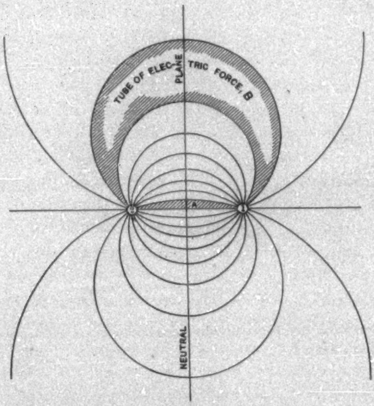

FIG. 27

This same state of things obtains at the other conductor. Each conductor is enclosed by a zone having a depth of a few inches within which the total stock of captured ions are actively engaged in a *double frequency* synchronous advance and retreat. The *view* here presented seems to be the only one that corresponds to all the evidence that has so far accumulated in regard to the in-phase loss current set up at sub-critical voltage. A close study of Mershon's Niagara results develops the facts that the loss produced by this current varies approximately as the square of the voltage and *as the square of the frequency*; that such loss is largely independent of the size of the conductors, their distance apart and whether they are solid or stranded. These results show clearly that stranding lowers the critical voltage because it lowers the tendency of the outgoing electrons at the cathode to core-up and make an early part-corona start by the process repeatedly referred to in this paper, but they do not indicate that stranding lessens the loss current below the critical voltage that starts part-corona.

Change in voltage wave-form is a factor related only to critical and corona voltages and not to the amount of the loss below critical voltage. Remembering the evidence that has been presented which shows that an increase in antecedent ionization, *i.e.*, an increase in the loss at sub-critical voltage increases the strength of the contractile envelopes about the migrating ions and their ability to start brushes or part-corona and thus to lower the critical voltage and remembering also what has just been said above in regard to the factors that control and develop antecedent ionization: It is clear that an *increase in high-voltage as such* irrespective of stress factors, *i.e.*, the diameters and distances apart of the conductors, will relatively lower the critical voltage. This is the chief reason why Mershon's Telluride and Niagara results, as to his designation of critical voltage, differ so much after due allowance was made for change in atmospheric density due to altitude. The differences are due entirely to natural causes The antecedent ionization in both cases are much the same at the same voltage. However, owing to the low barometer at Telluride the full corona starting voltage there, was but about *two-thirds* of the corresponding voltage at Niagara. The consequence is that the antecedent ionization loss at such voltage was only about *one-quarter* of the corresponding loss at Niagara, thereby elevating the critical voltage because the downward extent of the part-corona range was lessened.

e. Stranding and hard-drawing as factors that determine critical voltage and corona voltage.

In his Niagara Falls tests Mershon found that stranding the conductors in a given case raises the critical voltage quite appreciably above that of the same corresponding case wherein the conductors are solid having the same *over-all* diameter. He found also that the critical voltage is increased as the number of strands is increased when the same over-all diameters are retained beginning with seven strands at which no increase occurred.

This effect is undoubtedly due to the fact that any change in the electric field within the small corona striking distance from the conductor surface will cause a corresponding change in the critical voltage that starts part-corona. Part-corona starts at the same critical collision-ionizing stress as that required to start uniform corona, the difference being that in spots more or less regularly distributed over the surface of the conductor the field has been concentrated at sub-corona voltages to the critical stress density, starting corona at such spots and giving rise to the phenomenon of part-corona or brush discharge already often referred to. This field concentration has been brought about by the concentrated travel of ions forming cores that act as conductors to concentrate upon them the electric field and to deplete it elsewhere near the conductors.

The aggregate effect of increasing the strands in a conductor is to expand the electric stress in the thin but important corona-striking envelope of air covering the conductors and to make the effect of such expansion amount to more than the effect due the resulting increase in capacity caused by the stranding.

In the same series of high-voltage tests Mershon also found correspondingly that the effect of " hard drawing " is to increase the critical voltage. By hard drawing the atoms of the conductor are made to take up a more compact arrangement—particularly at the surface. One must expect this to interfere with the ease with which the free ions of the conductor can act their part in the process of ionization by impact. If this view is correct hard drawing raises the critical voltage by failing to maintain fully the stock of ions that carry the in-phase loss current set up at sub-critical voltages, upon the inverse magnitude of which, as shown above, the critical voltage, among other factors, depends.

f. Quantity of antecedent ionization a critical voltage factor.

This factor has been segregated by the application of first principles and by the study of a considerable range of high-voltage tests. In the final round-up of all controlling factors that could be found it has taken a very important place. It was desirable, therefore, to obtain evidence by some convenient form of high-voltage laboratory experiment that would determine its existence in a manner as direct as possible.

The following experiment was chosen for this purpose. A diagram of the apparatus and its arrangement as employed in the experiment is given in Fig. 28. In a large open laboratory building a pair of tinned steel telephone wires, approximately No. 12 B. & S. gauge, were mounted and insulated for high-voltage tests, approximately 13 in. (33 cm.) between centers, making a line about 50 ft. (15 m.) long, 12 ft. (3.6 m.) from the floor. These wires had been in service and exposed to the weather for a year or more. Their surfaces had captured and retained comparatively little radioactive emanations as one familiar with such matters could tell by watching the manner in which part-corona first made its appearance. The wires were therefore in a suitable condition for the purpose of the experiment. The actual critical loss-voltage value observed visually, was 58 kilovolts (effective sine-wave), 60 cycles. The previous use of the electrostatic cathode ray power diagram indicator had demonstrated that Mershon's value of critical voltage occurs at the first visual appearance of the part-corona brushes. Visual observation could therefore be relied upon fully for the purposes of the experiment.

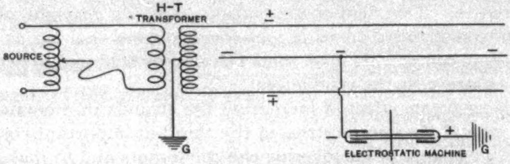

FIG. 28

In the plane of the conductors and midway between them a No. 30 B. & S. gauge bare copper wire was suspended and insulated for the application of high-voltage. It was connected to the negative terminal of an electrostatic machine, the positive terminal of which was grounded, as was also the middle of the high-tension transformer secondary. This electrostatic machine delivered to the wire about 0.00003 ampere at 10,000 volts. When no alternating high-voltage was applied to the line and corona was produced over the fine wire by operating the electrostatic machine on the application of the alternating high-voltage to the line, the corona on the fine wire disappeared; the discharge from it was then entirely dark. With negative discharge on the fine wire absent, a critical voltage of 58 kilovolts (effective sine-wave) was required to start the first small brushes; on elevating the voltage full corona appeared *promptly*. With the negative discharge on the fine wire present, the corresponding critical voltage was only 52 kilovolts; on elevating the voltage full corona developed much more *slowly* than it did with the discharge on the fine wire absent. One could set the voltage on the line at 53 kilovolts with no evidence of part-corona formation as long as the fine wire discharge was absent. Immediately on starting the fine wire discharge, the first stage of part-corona appeared. The experiment was varied by setting the line voltage just under the normal critical voltage, *i. e.*, at about 57 kilovolts with the fine wire uncharged; immediately on charging the fine wire by starting up the electrostatic machine, a heavy part-corona approximating the stage of full corona appeared.

The experiment demonstrated that an abundance of negative ions produced in the neighborhood of a high-voltage line will lower the Mershon critical voltage materially while it will change but little the voltage that develops full corona. Of itself an experiment of this sort would not amount to much; considered in connection with the fact that the critical voltage is lowered as the in-phase ionization current increases, it occupies a place of real value as a check upon ones understanding of these matters.

g. Captured emanation or " dirt " on the conductors as a critical voltage factor at the cathode only; *resulting effects in corona formation by continuous and alternating high-voltages*.

Mershon, Watson*, Whitehead† and others have found that dirt on the conductors will lower the critical voltage. Mershon and Whitehead used alternating voltages; the former employed parallel conductors in the open, the latter, closed concentric cylinders. The results of both agree and show that the effect of dirt on the conductors is to lower the critical voltage; White-

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*E. A. Watson, " Losses off Transmission Lines Due to Brush Discharge with Special Reference to the Case of the Direct Current." British Assn. Advancement of Sc. Winnipeg 1909 meeting advance copy. E. A. Watson " Atmospheric Losses from Wires under Continuous Electric Pressure." *Electrician* Sept. 3 1909 and Feb. 11 and 18, 1910.

†J. B. Whitehead, " The Electric Strength of Air." See TRANSACTIONS, A. I. E. E.. Vol. XXIX, p. 1159, 1910.

head concludes that it may be lowered as much as 33 per cent. Watson, using closed concentric cylinders and continuous high-voltages found in the particular test of dirty wire reported in his Winnipeg paper that the critical *negative* voltage was lowered as much as 50 per cent. He gives voltage current loss curves for the wire dirty and clean, showing that the dirt lowers the critical corona by concentrating the stress and starting part-corona at lower voltages than those required to start uniform corona on clean wires. When the conductor was subjected to positive, in lieu of negative continuous potential, dirt on its surface had little or no observable effect upon the value of the critical voltage and loss current set up when such voltage was exceeded.

There are two classes of " dirt " to be considered in this connection: (1) the one made up of very fine conducting material such as precipitated carbon and (2) the other, made up of non-conducting or partially non-conducting material, rich ionized molecules or particles, or radioactive emanations that are so easily captured from the atmosphere. It was known in advance that the second class of dirt would, when adhering to the surface of the cathode-conductor, become radioactive under the negative high-voltage stress and emit negative ions and therefore electrons that promptly become detached from such ions under great electric stress and thus concentrate the field over such patches of dirt starting thereat part corona at a lowered critical voltage.

There was, however, some doubt as to the behavior in this respect of dirt of the first class. The electrostatic power diagram indicator was, therefore, applied to a pair of parallel piano wires mounted at the centers of their enclosing cylinders and the 60-cycle alternating high-voltage noted that started the formation of a power card. This done the wires were coated each with a thin layer of fine carbon deposited from the flame of a candle mounted underneath by a wire carrier to which was attached a string and drawn forward slowly from end to end of each wire. The experiment was again repeated and it was found that the critical voltage had been increased from 22 to 24 kilovolts, evidently due to the effective increase in the diameter of the wire made by the envelope of fine conducting carbon. This result was accepted as satisfactory proof that dirt which is almost wholly made up of fine conducting material, *i.e.*, dirt of the first class, is not a factor in lowering the critical voltage.

A corona voltmeter was made by mounting a clean tapered brass conductor at the center of a cylinder of half-inch (12.7-mm.) mesh wire screen.* It is used for observing transient voltage. It stands in the open laboratory and after a time the surface of the brass rod must be cleaned to remove the captured emanations that cause its corona performance to be irregular. When it has not been cleaned for a time stout brushes appear at various places on the rod where there should be no corona. These brushes will always adhere to particular spots which when examined in the full daylight frequently can be hardly distinguished from the normal surface of the rod. The spots locate the presence of radioactive emanations that are easily removed mechanically. Once started they become centers about which preferential capture continues because of their own contribution to the electric field about the rod.

Doubtless all manner of dirt of the above second class will behave as these emanations behave because of the abundant ions that such material contains. In general the effect upon the alternating critical voltage and in-phase loss currents at higher voltages is much the same as that which is produced by the loss currents due to the stock of ions captured at sub-critical voltage. There are, however, no frequency and absolute potential factors connected with effects due to captured emanations and dirt as is the case with ions that are captured and held to cyclic orbits in the atmosphere about the conductors.

h. Form of the electrodes and resulting figure of the electric field as critical voltage and corona formation factors.

There are three classes of electrodes to be considered in this connection:

1. Concentric cylinders.
2. Small cylinder and plate—parallel mounted.
3. Small parallel cylinders.

The first two are used only for laboratory purposes. The concentric cylinders have been much used for the laboratory study of corona. By their use corona is developed only over the small central cylinder in the envelope of air immediately adjacent thereto which is subject to a uniform spreading stress in an amount that is exactly calculated from the dimensions. The high-voltage required to produce corona-forming stress is one-half or less than that which is required when wires or cables are used. Thus with a 125-kilovolt source, as great balanced stresses in the air about a conductor at the center of a cylinder can be produced as when 250 kilovolts are employed to stress the air covering a pair of conductors of the same size mounted parallel and at a suitable distance between centers.

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*Harris J. Ryan. Discussion giving details of this instrument. TRANSACTIONS A. I. E. E., XXVIII, II, p. 804, 1909.

Owing to the lower absolute potentials and the very small volumes of open air from which to capture a stock of ions, due to the facts and principles already established, the ionic loss currents at sub-critical voltages are exceedingly small; they can be detected only by the most delicate means. It is assumed that the high-voltage employed is alternating. The currents are too small to concentrate the field and start brushes at stresses lower than the one that will strike full corona; at all events nearly so. For the corresponding line of parallel wires or cables, to which is applied high-voltage in the open, this native ionization current would invariably be ample to concentrate the stress and thereby to lower the critical voltage. With concentric cylinders this antecedent ionization current is so small that it has little or no effect upon the critical voltage. There is practically no *part-corona range* and initial and corona voltages are not to be distinguished except possibly for the larger sizes of conductors *i.e.*, upwards from 0.3-in. (7.6-mm.) diameters.

The vapor-product in this form of high-voltage atmosphere loss-test can not be a critical voltage factor. The vapor-product is a critical voltage gauge only when the water vapor put into the atmosphere has been subject to a definite and rather abundant antecedent ionization, natural or artificial. The vapor-product will be discussed briefly as a separate topic. The results reported to the Institute by the author in 1904, already referred to, so far as they go, confirm these characteristics of the concentric cylinder tests.

Whitehead employed closed concentric cylinders, 60-cycle alternating high-voltage, central conductors of various diameters. From enclosed atmospheres at different temperatures, laden with moisture in known amounts over a wide range, he obtained results in abundant confirmation of the above understanding of the character of corona formation that is produced with concentric cylinders. Inherently, this method causes critical and full-corona voltages to be almost identical. In fact it practically eliminates the turbulent critical alternating voltage control factors contributed by the atmosphere in the open; the aggregate effects of these factors culminate in the behavior of the captured stock of natural ions whereby as already stated the electric field close to the wire is greatly disturbed, and concentrated in spots to such an extent as thereat to start part-corona and therefore to attain critical voltage at lower, and in some cases much lower, than the voltages required to produce full corona in the undisturbed electric field.

The concentric cylinder method constitutes a laboratory expedient wherewith to investigate the basic phenomenon in the corona problem, *viz.*, corona formation under known conditions as to figure of field and electric stresses. It eliminates all the disturbing factors that occur under practical conditions. It is purely a technical expedient for segregating and determining the character of the basic phenomena in corona formation under definite and decidedly limited conditions. The results that the method gives are an important aid to the *judgment* but are not to be employed for practical purposes without a knowledge of the *factor of safety* that must be applied to include the many turbulent, modifying elements that enter to determine critical voltage, part-corona range, and the ultimate culmination of full corona. This factor of safety is somewhat analogous to that which is employed in mechanical problems to include the turbulent elements that are inherent under practical mechanical conditions but which can not be given a rigid treatment as can the basic portion of the problem.

The position that the concentric cylinder corona test occupies should not be left without a further reference to the work of Watson who employed continuous high-voltages in this method. He found substantially the same critical voltage stresses at the surfaces of the wires that were found by Whitehead and the author using alternating high-voltages. His critical and full corona starting voltages were likewise coincident. His results confirm positively the conclusion drawn from fundamental facts and principles that corona formation, as such, is entirely independent of the frequency; they confirm likewise the conclusion that the concentric cylinder test determines corona formation under strictly definite and limited conditions as to amount of antecedent ionization and distribution of electric strain in the air about the conductor.

Watson's Winnipeg paper includes excellent photographs of the positive and negative coronas formed by continuous high voltages. The positive corona is uniform and flat against the surface of the conductor while the negative corona is irregular and lies more distant from the surface of its conductor. All this is quite as it should be in the light of first principles. The positive corona is formed by collision-ionization, due mostly to incoming electrons, that culminates in the air right next to the anode-conductor surface when the critical voltage has been exceeded. The negative corona is correspondingly due to collision-ionization produced also by electrons that are being expelled from the surface of the cathode-conductor where they have been liberated by the impact of incoming positive ions and by captured emanations; it culminates initially, not at the surface of the conductor but radially remote therefrom at *the corona striking distance*. The extra irregularity of the negative corona is due to the captured emanations which through their radioactivity concentrate the field about them, thereby lowering the critical voltage and forming a part-corona range at the cathode conductor, just as is the case correspondingly at both conductors when " dirty " and alternating critical high-voltages are applied.

Herein lie all the causes for the radical difference in the corona behaviors at anode and cathode in relation to critical voltage, part-corona range and initial full corona as modified by the presence on their surfaces of captured emanations and ionized " dirt ".

Moody and Faccioli employed the small cylinder and plate, parallel mounted, in their corona investigations reported to the Institute in 1909, reference to which was made earlier in this paper. Their corona tests were made in a small in-door enclosure securing thereby daytime darkness to permit visual observation of initial corona voltages. These voltages are *critical corona voltages* and not *critical loss voltages* and as such are comparable with the critical corona voltages observed by Whitehead and the author. They employed a 60-cycle 100 kilovolt (effective sine-wave) current. The small cylinder was connected to one terminal of the transformer, the remaining terminal of the transformer and the plate were grounded. Nothing is said in the paper apparently, in regard to the potential of the transformer case. In Fig. 2 of their paper the high-tension transformer employed is represented as mounted on the " floor ", uninsulated and quite near the test rod and plate. The conductivity of the floor under the circumstances is a considerable factor in determining the absolute alternating potential to which the air would be subjected in which the test rod is immersed.

With small conductor sizes having diameters near *one-eighth* inch (3.17 mm.) they found critical corona voltages sharply defined that are in agreement as to electric stress with the Whitehead and author's values obtained from concentric cylinders. With larger conductors they found critical corona voltages that were relatively higher. For a conductor having a diameter of *one-half* inch (12.7 mm.) with its center 18 in. (45.6 cm.) from the surface of the plate the critical corona voltage found was 95 kilovolts (effective sine-wave), while the corresponding value given by the author's formula as calculated by Moody and Faccioli is 83 kilovolts. This formula gives critical corona voltages that occur in the use of the concentric cylinders. When the distances between the conductor and plate is less the observed values are relatively higher than the calculated value.

Because the figure of the field in this case is considered to be quite exactly the same as that set up from one conductor to the " neutral plane " for the case of two parallel cylinder-conductors; because the field is in the aggregate much less regular than the field between the corresponding concentric cylinders; and again because the whole arrangement is apparently much more open than the concentric cylinders closed or open, it was at first surprising that this method should give critical corona voltages which are decidedly higher than those given by the concentric cylinders. Particularly is this so for the larger diameters whereat the field in the corona striking zone next the conductor surface also begins to be unbalanced partaking of the general character of the field. The observed and calculated values, using the authors formula for the latter, as obtained by Moody and Faccioli in these experiments are taken from page 774, Fig. 3, and page 775 of their paper and tabulated below:

DIAMETERS OF CONDUCTORS IN INCHES

	0.125	0.125	0.25	0.25	0.375	0.375	0.50	0.50
Distance inches	Kilovolts obs.	Kilovolts calc.	Kilovolts obs.	Kilovolts calc.	Kilovolts obs.	Kilovolts calc.	Kilovolts obs.	Kilovolts calc.
9	36.5	38.3	55.0	50.5	70.0	61.2	85.0	71.5
12	37.5	40.5	58.5	53.5	76.0	65.0	90.0	76.5
18	42.0	43.0	62.0	57.7	81.0	70.3	95.0	83.5

The calculated values for the *one-eighth* inch (3.17 mm.) conductor were added by the present author using the new formula derived toward the close of this paper.

Moody and Faccioli followed up the causes of these discrepancies by undertaking many interesting and instructive experiments. In one set of such experiments they used concentric cylinders open ended. The inner radius and length of the outer cylinders were 5 in. (12.7 cm.) and 18 in. (45.6 cm.). The test conductor was mounted at the center of this cylinder and connected as always to one terminal of the high-tension transformer, the other terminal and outer cylinder were grounded. The values observed herewith and those correspondingly calculated by the present author using his later formula are given in the following table:

Diameter inch.	Observed by Moody and Faccioli Kilovolts*	Calculated by the author Kilovolts*
0.125	24.0	30.2
0.250	36.5	38.5
0.370	47.5	45.3
0.500	54.5	51.6

*Effective, sine-wave potential.

If diameter critical corona voltage curves were located with these values they would intersect. These results show conclusively that the air inside the cylinder was subjected to a composite electric stress due to the potential difference between the cylinders and the absolute potential of the air in which the open cylinders were immersed. An erratic migration of ions occurred causing corresponding changes in the normal ionization of the air within the outer cylinder and in the stresses that strike corona adjacent to the conductor surfaces.

(1) In the concentric cylinder tests of Watson, Whitehead and the author the air between the cylinders was not subject to disturbances by contact with an outer atmosphere at an uncertain potential, and the critical corona stress results are in remarkable agreement although the construction and methods in most other respects differed greatly. (2) When we undertook critical-loss voltage tests on a three-phase high-tension laboratory line charged from two open delta-connected 20-kw., 60-kilovolt 60-cycle transformers, although the three alternating potential differences were practically balanced as to phase and voltage, the resulting corona formation was remarkably unbalanced because of the disturbances of the neutral potentials caused by the electrostatic relation of the transformer cases, high-voltage circuits, three-phase line, "ground" and surrounding atmosphere.

This can probably be overcome by resistance loads properly applied; time has not as yet permitted this to be tried out.

These two sets of evidence together with the general principles involved demonstrate conclusively the cause of the erratic corona behavior found in the above tests using the rod and plate. It is doubtless possible to shield the rod and plate electrode from uncertain potential interferences with the stresses and migrating ions, in which event the Moody-Faccioli evidence indicates that this form of test will yield much the same critical corona stresses as those obtained by the use of the concentric cylinders with the surrounding normal zero potential undisturbed. In any event the parallel rod and plate, while offering greater structural and experimental convenience, can not employ on the one hand such a definite limited stock of natural ions as the concentric cylinders, while on the other hand it does not nclude all of the factors that enter when the parallel cylinders are used in the open so as to obtain critical loss and critical corona voltage corresponding to the conditions of practical operation.

The factors that enter when the electrodes are parallel cylinders mounted in the open atmosphere, indoors or out according to the kind of air to be studied, have already been considered. Some special examples will be considered below as a separate section of the paper. This is the only form of test that yields the composite results that are applicable to practice.

i. The power transmission current as a possible critical voltage factor.

The magnetic field set up about the transmission conductors in concentric zones of maximum strength at the surface of the conductor will have some influence in determining the value of the critical loss voltage. There is abundant evidence that anything which alters or disturbs the normal movements of the electrons very near to the surface of the conductors will modify the critical loss voltage. Electrons, when driven through a magnetic field, are everywhere turned at right angles to the direction of the field. The actual directions are the same as for the deflections of equivalent currents. The field that the power current sets up will cause the electrons to be forced out or drawn in by curvelinear routes near the surfaces of the conductor. From the general nature of the phenomena one must expect that this cause will effect a certain increase in the critical loss voltage —perhaps comparable with that caused by stranding the conductors.

j. The vapor-product as a critical loss voltage factor found by Mershon at Niagara Falls.

When one considers the evidences that establish the place that natural ionization occupies in determining the extent and character of the energy loss in the atmosphere about high-voltage transmission lines; when it is remembered that the vapors rising from great water falls are highly ionized; and when the fact is included that artificial changes in the vapor product unaccompanied by corresponding ionization changes cause little or no change in critical loss voltages one is forced to conclude that the vapor-product at Niagara Falls was a pretty good gauge of an extra natural supply of ions that were carried to the region of test by the vapors rising from the near-by falls. One must, therefore, expect to find the vapor-product acting the role of an ionization gauge in similar localities and along ocean shores, etc.

k. Absolute potential and phase relations as critical voltage factors. (Polyphases, balanced and unbalanced.)

It was expected in advance that a four-wire, two-phase line wherein the conductors are mounted at the corners of a square, each phase occupying a diagonal, would render critical loss and corona voltages identical with those rendered on one phase and the other cut-out. This was tried out and found to be so. When both phases are applied to the lines the instantaneous voltage of the one is zero when the other is maximum and engaging in corona formation, if the critical voltage has been exceeded. From first principles it was expected that each conductor held its captured stock of ions so close in as not to contribute to the effective stock of the other. The result of the experiment confirmed this understanding of the matter.

The conditions about a three-phase line are somewhat different in that only one conductor comes to maximum potential at a time, and for this reason it was expected in advance of actual trial that when any sort of unbalancing was present the individual conductors would have differing opportunities to capture a stock of ions. In advance of actual trial this feature was rather dimly realized from fundamentals. Our facilities afforded an adjustable three-phase 60-kilovolt, 60-cycle source only by means of two open-delta connected, 20-kw. transformers. The No. 12 B. & S. gauge tinned and weathered telephone wires were mounted for the application of high-voltages inside a large open monitor type laboratory building. The length of line was about 130 ft. (39.6 m.); the center to center separation of the three conductors was 12.5 in. (30.5 cm.). The high voltage delivered from the open-delta-connected transformer secondaries was adjusted to a true three-phase condition at the voltage maxima both as to phases and magnitudes and then checked by needle spark-gap.

The transformer cases were thoroughly insulated by mounting the transformer on a frame supported by a bank of standard 30-kilovolt insulators. The terminals of the two transformers are designated 1 and 2′ and 2″ and 3 respectively. 2′ and 2″ were joined making a common terminal 2 so that the three-voltages were delivered from between 1, 2 and 3, in the usual fashion, to the line conductors correspondingly numbered 1, 2 and 3. The first set of observations were made by applying the high-voltage to the line with the transformer cases insulated. The voltage was gradually raised and the corresponding values noted at part-corona started on each line conductor. The results obtained were as follows:

TRANSFORMER CASES INSULATED

Conductor	Critical loss effective sine-wave kilovolts
1	33.6
2	49.6
3	29.2
	Single phase (2:3 cut out)
1:2	46.4

The test when repeated with the transformer cases grounded yielded the following results:

TRANSFORMER CASES GROUNDED

Conductors	Critical loss effective sine-wave kilovolts
1	35.6
2	50.2
3	32.0

The above test was then repeated one change only having been made, *viz.*, two of the three connections between the source and the line were reversed.

TRANSFORMER CASES GROUNDED
Leads 1 and 2 to line reversed

Conductors	Critical loss effective sine-wave kilovolts
1	46.0
2	33.6
3	28.8

These results bring out clearly the importance of the absolute alternating potential of the line conductors in relation to their potential differences. The few hurriedly made tests demonstrated promptly that to go into the matter fully would constitute a considerable undertaking. Work along this line had to be given up, therefore, for the time being, as the purpose of the present undertaking was to be strictly limited to an effort to secure some hold upon the fundamental facts and principles that have a general application in these matters.

In concluding this sub-topic attention is called to the relation of these results to those already referred to of Moody and Faccioli who also introduced the absolute potential factor by operating with one terminal of their high-voltage transformer grounded.

IV. Conclusions and Table of Corona Formation Data Obtained from High Voltage Line Tests

The fundamental feature of corona is the formation of a collision-ionization envelope about the conductors of the high-voltage transmission line. Under normal atmospheric conditions, *i.e.*, barometer 29.5 in. (750 mm.) of mercury and temperature 70 deg. fahr., the critical stress required to start collision ionization when regularly distributed, is 76 kilovolts per in. (30 kilovolts per cm.) at the critical striking distance, *a*, Fig. 2, from the surface of the conductor. It varies directly as the barometric pressure and inversely as the absolute temperature.

In addition to ionization by collision as the *basic factor* in corona formation, there is the complex and entirely turbulent *irregularity factor* that is made up for a given case, in whole or in part of the following elements, given approximately in the order of their importance:

1. Irregularity of electric fields beyond the atmospheric envelope covering the conductor in which the initial corona strikes.

2. Earth connection; on one side or at the neutral of the high-voltage source.

3. Excess or lack of natural or antecedent ionization of the atmosphere.

4. Captured ions and radioactive emanations at the conductor surfaces.

5. Mechanical form of the conductor surface affecting the uniformity of the electric field within the thin corona striking envelope covering the conductor.

6. Physical character of the conductor surface as to hardness and molecular structure that affect the impact ionization facility.

7. Magnetic fields about the conductors due to the power currents they transmit.

8. Stray factors, *viz.*, ultra-violet light, *et cetera*, none of which are important.

For convenience in referring to the parts of a corona voltage loss curve, the following terms are employed: It is assumed that the losses in watts are the ordinates to the curve and the voltages the corresponding abscissæ: That portion of the loss curve developed at voltages below the critcal voltage will be called the *lower, part*, the succeeding portion covered by the sharp upward turn will be called the *elbow* and the remaining portion will be called the *upper part*. The losses expressed by the lower part, elbow and upper part are designated as losses by *convection*, *part-corona*, and *corona*, respectively.

The convection current is small and of little importance on its own account, except at very high voltages, high altitudes or high frequencies. However, the convection loss current interferes considerably with the regularity of distribution of the electric field very near the surfaces of the conductors—a vital controlling factor in corona formation. The larger the convection current the greater is this effect of strengthening the field in spots at the surface of the conductor where part-corona will start at a correspondingly lower average stress and therefore line voltage. The character of the lower part of the corona loss curve is, therefore, of much indirect importance. The convection current increases with the amount of natural or antecedent ionization—at what rate is not yet definitely known; it also increases approximately as the altitude and as the square of the voltage and frequency.

The form of the elbow, *i.e.*, the changing rate at which part-corona begins and merges into corona as the voltage is increased is directly related to the amount of the convection current. The larger the convection current in a given case the lower will be the corresponding critical voltage at which part-corona will start and the more gradual will be the rate at which such part-corona will turn into a full corona as the voltage is increased; *i.e.*, the steeper the lower part of the loss curve the longer the elbow.

The result in the aggregate is that, whereas critical voltages at which part-coronas begin are greatly and irregularly affected by these turbulent factors, such factors have a much smaller and more definite effect upon the voltage at which part-corona ceases and corona begins. Full corona formed about parallel transmission conductors in the open is never as regular as that which is formed about the small inner cylinder by laboratory test. The result is that corona begins on a transmission line at about 80 per cent of the corresponding corona voltage found by the concentric cylinders laboratory test. This factor applies to an ungrounded circuit and to round solid, or seven-strand conductors. Grounding the circuit may change this factor considerably, Smith's 1901 results show that a neutral ground may under some circumstances raise the value considerably while it is reasonable to expect in the light of all the available evidence that a high potential ground may lower it some. Stranding the conductors interferes with the concentration of the convection current at or near their surfaces. It increases the number of ion-cores or current streams and thus lessens the irregularity of the surface stress, raises correspondingly the critical voltage, lessens the part-corona range and in the end lowers the above irregularity corona factor; *i.e.*, for stranded conductors and a given pitch of the lower part of the loss curve the elbow is sharper and shorter and the upper part steeper compared with corresponding solid conductor results.

The elbows of the loss curves cover wide voltage ranges—from 5 to 50 per cent of the initial corona voltage. Owing to the fact that a long elbow is followed by a slow rise in the high-voltage loss curve and *vice versa* these variations are compensated to a considerable extent. An average of 10 per cent of the initial corona voltage may be taken for practical purposes to cover the length of the elbow under ordinary conditions.

Thus a rational formula in part for predicting critical and corona voltages may be derived by employing these factors as follows:

Let E_c be the critical corona voltage.

E_{pc} be the critical part-corona voltage.

E_{cc} be the critical corona voltage due to critical stress, critical striking distance and a given density of air; *i.e.*, the critical corona voltage obtained by laboratory test using concentric cylinders.

k_c be the *irregularity factor* for transmission line critical corona voltage, *i.e.*, $k_c = \frac{E_c}{E_{cc}}$.

k_{pc} be the part-corona factor, *i.e.*, $k_{pc} = \frac{E_{pc}}{E_c}$.

k be the irregularity factor for critical loss voltage; *i.e.*, $k = k_{pc}\, k_c$.

E_{crit} be the *crictical loss voltage.*

i.e.,

$$E_{crit} = k\, E_{cc} = k_{pc}\, k_c\, E_{cc}$$

As stated above under all ordinary circumstances:

$$k_c = 0.8;\ k_{pc} = 0.9;\ \text{and}\ k = 0.8 \times 0.9 = 0.72$$

i.e.,

$$E_{crit} = 0.72\, E_{cc}$$

This does not place the critical voltage as low as the exact value where convection loss transfers to part-corona. The convection loss is small; it is given approximately by the following equation:

$$P = 2.0 \times 10^{-6} f^2 E^2$$

wherein P = watts per 1000 feet, single phase line.
f = frequency.
E = kilovoltage.

Example: $f = 60$ $E = 100$. Substituting $P = 72$ watts, or 380 watts of convection current loss per mile of single-phase line.

The change from convection to part-corona loss is always very gradual. The entire part-corona range multiplies the inevitable high-voltage loss by convection ***not more than five*** times. The above ratio

$$\frac{E_{crit}}{E_c} = 0.9$$

places the critical voltage high enough so that part-corona has increased the loss by an amount approaching the corresponding convection loss at the same voltage. Where corona is the voltage limiting factor, a few part-corona brushes will cost less than the increased cost in transmission caused by lowering the voltage to a point where they are completely eliminated. The factor $k_{pc} = 0.7$ and therefore $k = 0.56$ would eliminate brush discharge completely but at too great a cost. For this reason $k_{pc} = 0.9$ is chosen as a typical value based on a convection and brush discharge or part-corona loss less than one kilowatt per mile of a 100 kilovolt transmission line for usual conditions as to ionization, low altitude, temperature, etc.

No consideration is made here of the effect of part-corona on the durability of the conductor. Matters of that sort are not herein considered.

The factors $k = k_c \,.\, k_{pc}$, should be chosen with the same care and judgment as are employed in the selection of safety factors for structural design where turbulent elements enter along with those of a definite fundamental character. The critical loss-voltage factor $k = 0.72$ *i.e.*, $k = k_{pc}\, k_c = 0.9 \times 0.8 = 0.72$ is perhaps as safe a factor as any to be used without the aid of a judgment experienced and trained in these matters.

The rational value of the initial uniform corona voltage, E_{cc}, employed above is derived as follows:

E_{cc} is that voltage which will establish critical stress factor in a zone about the conductor at a distance from its surface equal to the corona striking distance. The normal critical stress is 76 kilovolts per in. (30 kilovolts per cm.) and the normal critical striking distances, a, in relation to the conductor diameters are obtained from the curve in Fig. 2. The electrical stress at the surface of a transmission conductor in kilovolts per in. is the ratio of the capacity per square inch of the surface of such conductor to the capacity of an inch-cube of air—the latter being 2.244×10^{-13} farads, thus kilovolts per in. surface stress factor =

$$\frac{C \times 10^{-6}}{1000 \times 12 \times \pi\, d} \times \frac{1}{2.244 \times 10^{-13}} = \frac{10^3}{2.70\, \pi} \quad \frac{C}{d}$$

wherein C = capacity of line in microfarads per 1000 feet.
d = diameter of conductor in inches.

The voltage that will produce a stress of 76 kilovolts per in. at the distance, a, from the conductor surface

$$E_{cc} = \frac{76}{\sqrt{2}} \cdot \frac{2.70\ \pi}{10^3} \cdot \frac{d+2\ a}{C}$$

$$E_{cc} = .455\ .\ \frac{d+2\ a}{C} = \qquad (1)$$

the kilovolts, (effective sine-wave) required to start *uniform* corona about cylindrical clean conductors in the normal atmosphere wherein the values of a, C and d are given as defined above.

The corresponding critical loss, kilovolts for all ordinary conditions are

$$E_{crit} = .328\ .\ \frac{d+2\ a}{C} \qquad (2)$$

The corresponding expression giving the critical loss-kilovolts for any set of conditions is

$$E_{crit} = .455\ .\ k\ .\ \frac{17.9\ b}{459+t}\ .\ \frac{d+2\ a}{C} \qquad (3)$$

wherein: E_{crit} = critical loss kilovolts, (effective sine-wave).
k = $k_{pc} \times k_c$, factors selected by judgment guided by the results of practical tests and experience.
d = outer diameter of wire or cable in inches.
a = corona striking distance obtained from curve in Fig. 2.
b = barometer, inches of mercury.
t = temperature, deg. fahr.

All available data relating to corona formation obtained from high-voltage line tests are given in the following tables. The values headed " Critical Uniform Corona Voltage, Calculated " were determined by means of the above equation, No. 3, omitting the factor, k. Fig. 29 is a reproduction of a photograph of the part-corona display on the 110-kilovolts transmission line in Michigan upon which the tests were made by Foote. Other items of interest connected with these data not subject to tabulation are given in footnotes.

TABLE I.

Number	Month, test	Year published	Name	Place	Altitude, feet	Barometer, inches	Temp. deg. fahr.	Conductors							Capacity m.f. per 1000 feet	Critical loss-voltage; kilovolts (effective sine-wave) observed	Critical corona voltage: kilovolts. Effective sine-wave observed	Critical uniform corona voltage kilovolts (effective sine-wave calculated§	k_c	k_{pc}	k	Remarks
								Circuit			Section cms.	No. of strands	Diameter over all inches	c:c inches								
								Length	Phases	Cycles												
1		1897	Mershon	Telluride, Col.	8,000	21.5†	60†	Feet 11,720	1	60	24,000	1	0.156	52	0.00131	54.0	56.0	73.6	0.76	0.96	0.73	In Rocky Mountains
2	2 p.m. May 14	1901*	Smith‡	Worcester		29.5	70†	250	1	60	10,400	1	0.102	30	0.00133	64.0	69.5	76.0	0.91	0.92	0.84	On Worcester Campus
3	May 28	1902*	" ‡	"		"†	75†	"	1	60	66,400	1	0.258	48	0.00143	95.0	107.0	123.5	0.86	0.89	0.76	" " "
4	May 29	1902*	" ‡	"		"†	75†	"	1	60	66,400	1	0.258	24	0.00162	107.0	123.0	109.0	1.13	0.87	0.98	" " "
5		1908	Mershon	Niagara Falls	660	29.5†	70†	1,000	1	73	10,500	1	0.102	55	0.00121	58.0	61.0	76.0	0.80	0.95	0.76	Vapor Product 0.2
6		"	"	"	"	"	70†	"	1	73	20,740	1	0.144	55	0.00128	77.0	81.0	96.5	0.84	0.95	0.80	" " "
7		"	"	"	"	"	70†	"	1	73	34,600	1	0.186	55	0.00133	80.0	86.0	105.5	0.81	0.93	0.76	" " "
8		"	"	"	"	"	"	"	1	73	41,800	19	0.234	55	0.00138	88.0	89.0	120.5	0.74	0.99	0.73	" " "
9		"	"	"	"	"	"	"	1	73	41,750	37	0.235	55	0.00138	90.0	90.5	121.0	0.75	0.99	0.74	" " "
10		"	"	"	"	"	"	"	1	73	42,910	7	0.235	55	0.00138	92.5	93.0	121.0	0.77	0.99	0.76	" " "
11		"	"	"	"	"	"	"	1	73	103,850	7	0.366	29	0.00168	Approx imated 106.0	——	136.2	0.78	1.00	0.78	" " "
12		1910	West	Central Colorado Power Co's. Line: Glenwood, Dillon Denver and Boulder	11,500	18.2†	70†	181 Miles	3	60	83,690	6	0.354	124	0.00129	77.0	——	107.0	—	—	0.72	One transmission line; operating at 100 kilovolts.
12		"	"		13,300	16.5†	70†		3	60	105,500	6	0.398	124	0.00133	77.0	——	103.0	—	—	0.75	
13		"	Foote	Grand Rapids, Mich		29.5†	70†	50	3	60	66,370	6	0.316	96	0.00132	110.0	——	156.0	—	—	0.70	Operating at 110 kilovolts
14		"	"	Flint, Mich.		"	"	125	3	60	105,500	6†	0.398	120†	0.00132	135.0	——	184.0	—	—	0.73	135 kilovolts proposed
15		**	Ryan	Stanford	100	30	70	Feet 130	1	60	7,210	1	0.085	12.5	0.00151	47.0	——	60.0	—	—	0.76	Test made in monitor type open laboratory building
16		**	"	"	"	30	70	130	1	60	83,700	7	0.331	36	0.00157	106.0	——	135.0	—	—	0.76	

*Not published. †Assumed. ‡Middle of high-voltage transformer grounded. §Equation No. 3 used, omitting k.

TABLE II.

No.	Name and place	Loss by convection	Loss curve				Remarks
			Elbow		Upper part		
			Curvature	Length	Slope	Character	
1	Mershon Telluride	Normal	Sharp	Short	Steep	Nearly straight	Short line at high altitude
2	Smith Worcester	"	Very sharp	Very short	"	Straight	Neutral grounded; probably responsible for high convection loss and high critical loss and high critical corona voltages.
3	"	Above normal	Sharp	Short	"	Nearly straight	
4	"	Large	Sharp	"	Very steep	Straight	
5	Mershon Niagara	Normal	Sharp	Short	Steep	Nearly straight	In this series the relation of loss by convection and loss by part corona is well brought out. With small conductors and, therefore, low voltages, loss by convection is much less than loss by part-corona; with the larger conductors and, therefore, higher voltages, loss by convection equals loss by part-corona, causing $k_{pc} = 1$ and $k_c = k$
6	"	"	Normal	Normal	Normal	Nearly straight	
7	"	"	"	"	"	"	
8	"	"	Sharper than normal	Shorter than normal	Steep	"	
9	"	"	"	"	"	"	
10	"	"	"	"	"	"	
11	"	"	"	"	"	"	
12	West Cent. Col.	—	Normal	Normal	Steep	Nearly straight	181-mile 100-kilovolt line open; no receiver connections
12	"	—	Sharp	Short	Very low	"	Same line operated with end receiver loaded
13 and 14	Foote Michigan	The only data available in regard to these Michigan high-voltage lines are those reported in the Electrical World, Vol. 50, p. 850, 1907 and Vol. 54, p. 664, 1909 and by D. B. Rushmore, General Elec. Review, XII, p. 86, 1909, for the Grand Rapids 110-kilovolt transmission; Elec. World, Vol. 56, July 14, 1910, p. 86 for tests and data relating to the proposed 135-kilovolt Flint, Mich. transmission. They are rather incomplete for checking corona factors.					

No. 4. This case is of especial interest. The results indicate an unusual electrical state of the atmosphere: Heavy ions, few in number, migrating mostly to the ground urged on by the electric field to earth of the high-voltage line combined with the natural electric field of the earth. The results of this test are the only ones available that show a large convection current, evidently passing to ground, and a small degree of natural ionization about the high-voltage line conductors as shown by the establishment of a remarkably uniform corona requiring a voltage to start it that is almost as high as the standard given by equation 3 and by the concentric cylinders laboratory tests. In fact the results of all three of these Worcester tests wherein the neutral-ground connection was used show the influence of such connection. The aggregate effect of which has been to render higher than normal values of the critical loss-voltage irregularity factor, k.

No. 11. The critical loss-voltage of 106 was located by exterpolating the original curve somewhat so as to locate a high-voltage loss equal to double the convection current loss. Doubtless an error of as much as two per cent may have been introduced in this manner.

No. 12. Mr. E. L. West, as assistant general manager for the Central Colorado Power Company, found that the corona loss on this line was much higher with the receiver load off than with it on. He found that with nothing whatever connected to the line a station voltage of 77 kilovolts (effective sine-wave), applied at Shoshone caused part-corona to start on the line conductors over the passes, and that as the voltage was increased the corona loss increased with almost the same rapidity that it would if it had been started simultaneously over the entire 181 miles (291 km.) of line and attained a value, due to corona alone, of 16 kw. per mile (10 kw. per km.) at a station voltage at Shoshone of 105 kilovolts. West and his co-worker Mr. Chas. S. Ruffner made an extensive study of this behavior of the line and found:

1. With the receiver load on, the corona formation was limited to the line-sections through the passes and similar high elevations: that the corona loss started at the same voltage, *viz.*, 77 kilovolts (effective sine-wave), and increased very slowly, attaining a value due to corona along at 105 kilovolts, of about 4 kilovolts per mile (2.5 kilovolts per km.) for the total line, or about one quarter of the loss that occurred with the line open at all points.

2. That the great excess corona loss which occurred when full voltage was applied to the line entirely open, occurred largely on the Denver-Boulder section.

A study of West's data very kindly furnished the author for such purpose, was made having in mind the first principles that must apply in matters of this sort. A summary of the essential line data is given in the accompanying table.

It is seen that the high altitudes occur in the 60-mile (965 km.) section that includes the passes and which constitutes roughly the middle of the three 60-mile sections. The facts and principles presented in this paper show that corona and the electric arc are the same phenomena displayed merely with different proportions as to voltage, current and form of electrodes. The corona formed in the middle section when the line voltage is above 77 kilovolts acts the role of a *singing arc* to detach energy from the main source and send it oscillating through the *induction-condenser circuit of the Denver end section* at a frequency due to its natural period. The resonance develops great wave distortions in the normal line voltage of the end section. High frequency circulating currents are set up and the highly distorted voltages develop maximum values that exceed the critical corona voltages. Thus as in all resonant effects the up-building of the circulating currents ceases when the losses chiefly due to the corona formed in the Denver section balance the rate at which the corona in the middle section acting as a singing arc can detach energy from the station at Shoshone. Doubtless as soon as the process starts, it goes into turbulence, *i.e.*, the corona wherever formed takes up the role of the singing arc and acts at the same time as a brake on its own behavior.

SHOSHONE-DILLON-DENVER-BOULDER 100-KILOVOLT, 60-CYCLE THREE-PHASE TRANSMISSION LINE OF THE CENTRAL COLORADO POWER CO.

Total miles	Location	Miles in section	6-strand cable B. & S. gauge	Elevation		
				Average feet	Peaks	
					Width miles	Top elevation
0	Shoshone	—	—	6,000	—	—
		52	0	8,000	—	—
52	Hagerman Pass	—	0	10,500	2.5	12,000
		23	0–1	10,000	—	—
75	Fremont Pass	—	1	—	—	11,500
		34	1–0	10,000	—	—
109	Argentine Pass	—	0	12,000	5.5	13,500
		16	0	11,000	—	—
125	Three Peaks	—	0	11,000	16.0	—
		28	0	7,500	—	—
152	Denver	—	0	5,300	—	—
		29	1	6,000	—	—
181	Boulder					7,800*

*Peak near Boulder.

Nos. 13 and 14. Lines of the Commonwealth Power Co., J. B. Foote, electrical engineer, Jackson, Mich. (13) Grand Rapids, 110-kilovolts and (14) Cook-Flint 135-kilovolts (proposed) transmissions. Tests were made by Foote on the Grand Rapids line from which factors were determined for computing the critical loss-voltage (one kw. approximately per mile, at 135 kilovolts) for a three-phase number *o* conductor. It is proposed for this line to operate well into the part-corona range. That this is actually done on the 110-kilovolt Grand Rapids line may be seen by a glance at the photograph of this line taken at night in normal operation, reproduced in Fig. 29, kindly loaned for the publication of this paper by Mr. D. B. Rushmore.

Nos. 15 and 16. These tests were made at Stanford primarily for the purpose of comparing the corona losses indicated on the screen of the electrostatic power-diagram indicator with the visual effects. They were not primarily undertaken to secure results to be placed in the above table. When the table was prepared it seemed as though it might be well to add the results of these tests because they were obtained from thoroughly insulated lines mounted in a large indoor space and in a climate and at a season wherein the atmosphere is known to be at a normal state of ionization in the open.

Conclusions In Regard to the Open Atmosphere as an Insulator.

1. Ionization and the travel of ions under electric stresses are the causes of failure of the open atmosphere as an insulator and they are the cause of corona formation.

2. All ordinary failures of the atmosphere under stress are developed through ionization by collision which can be started under usual high-voltage electric stresses through the presence of some natural or antecedent supply of ions.

3. Variation in the supply of natural ions in open air is the cause of the erratic variation of critical loss-voltages. Such variations have little effect upon the values of the part-corona voltage that has increased the atmosphere loss by the small amount equal to the loss caused by the inevitable ion-convection current.

4. The figure of the electric field about the high voltage conductors determines the facility with which the migrating ions will concentrate the electric stress near the surface of the conductor and thus render the resulting corona irregular at all stages, causing it to be started and to be maintained at correspondingly lower voltages.

5. The turbulent elements introduced by variations in the amount of natural ionization have so small an effect upon the corona forming voltages, and the field irregularity factor above referred to is so nearly constant over a wide range of conditions, that the rational formula as developed should be found dependable to a reasonable extent.

6. The term "*dielectric strength*" as applied to the open atmosphere, from the inherent nature of things, can have no definite meaning.

7. The rupturing strength of the normal atmosphere rests upon two factors only, (1) quantity of ionization produced by the rupturing voltage, (2) the distance between the electrodes. The rupturing gradient varies from 300 kilovolts per in. (120 kilovolts per cm.) at lowest ionization to 3 kilovolts per in. (1.2 kilovolts per cm.) at highest ionization with no indication

that the limits at either end of this range have as yet been found.

Conclusion in Regard to Dry Transformer Oil As an Insulator.

1. The failure of the oil as an insulator is due to ions liberated by the electric stress from the supply of free ions in the metals of the electrodes.

2. The electric stress required to detach ions from metals to the oil is much lower than the corresponding stress for a gas.

3. The further conclusion follows necessarily that a compressed gas must, in regard to *insulating quality alone*, be superior to oil.*

APPENDIX

[*Reprinted from* SCIENCE, *N. S., Vol. XXXII, No.* 826, *Page* 608, *October* 28, 1910]

THE NATURE OF ELECTRIC DISCHARGE†

At a meeting of the Academy of Science of St. Louis, on October 17, the writer presented photographic plates which strongly confirm conclusions reached in former papers.[1] Pin-head terminals rest with their rounded heads upon the film of a photographic plate. Their distance from each other is about 7 cm. One terminal is grounded in the yard outside of the building. The other leads to a variable spark-gap at the negative terminal of an 8-plate influence machine, the positive terminal being grounded on a water-pipe. With very short spark-gaps, the passing of a single spark produces discharge images immediately around the pin-heads. Increasing the spark-length enlarges the images, which are in the nature of brush discharges. The negative glow around the pin-head which communicates with the negative terminal of the machine increases very little in diameter, and the discharge lines in it are radial. The discharge lines around the grounded pin-head for short sparks follow approximately the lines of force. With longer sparks

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*In addition to the references already made the author acknowledges the great assistance he has received from Professor Ernest Merritt of Cornell University, Professor Francis E. Nipher of Washington University, and Professor F. J. Rogers of Stanford University; likewise the hearty helpful coöperation of his co-workers, Professors Charters and Hillebrand and of the authorities of Leland Stanford University whose cordial approval of work of this kind made the necessary experimental facilities possible.

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[1] *Trans. Acad. of Sc. of St. Louis*, XIX., Nos. 1 and 4.

†See Figs. 11, 12*a*, 12*b*, 13, 14*a*, 14*b* and 14*c* of the present paper.

they are somewhat distorted, as if beaten back by a blast from the opposite or negative terminal. As has been suggested in the papers referred to these discharge lines in the "positive column" are drainage lines, along which Franklin's fluid is being conducted into the positive or grounded terminal. The portions of the air molecules which constitute the stepping stones for the negative corpuscles are urged in a direction opposite to that in which the negative discharge is flowing, thus promoting the lengthening of the drainage lines. Many hundreds of plates have been exposed in an attempt to adjust the spark-gap so that these drainage lines would end just outside of the negative glow without reaching it. In this way the length of these lines may be gradually increased until they approach the dark space around the negative glow. This dark space is a region where convection of atoms which have been supercharged within the negative glow are urged by convection away from the negative terminal. If the drainage lines reach this convection region, they cross it and reach the negative glow. It has thus far been found impossible to have them end within this Faraday dark space. If the spark-gap at the machine is so adjusted that only one or two drainage lines reach the negative glow, these lines will unite end on with the radial discharge lines of the negative glow. At the same time there is a distortion in the lines at and near their union, which reveals the commotion produced by the opposing "electric winds."

If now the spark-gap at the machine be slightly increased, other drainage lines reach the negative glow. They cross its radial discharge lines, and even extend beyond the negative terminal. In a few cases the entire area of the negative glow is traversed by these drainage lines. It is evident that we have here the same conditions that Goldstein found in the vacuum tube. These drainage lines are the canal rays of the vacuum tube.

This explanation of the nature of electric discharge enables us to understand why the positive column in a vacuum tube follows the tube in all of its windings and bends. It is not a convection column, but a drainage column. It is a conduction column. The conditions are different from those in a copper wire, in that the parts of the atoms which constitute the conductor are in gaseous form, and are capable of yielding to the force which urges them in a direction opposite to that in which the negative corpuscles are being urged.

FRANCIS E. NIPHER.

A communication presented at the 255th Meeting of the American Institute of Electrical Engineers, New York, January 13, 1911.

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HIGH-VOLTAGE LINE LOSS TESTS MADE ON THE 100-KILOVOLT 60-CYCLE 180-MILE TRANSMISSION LINE OF THE CENTRAL COLORADO POWER COMPANY

[COMMUNICATED TO HARRIS J. RYAN BY E. L. WEST AT THE REQUEST OF THE HIGH-TENSION TRANSMISSION COMMITTEE OF THE A.I.E.E.]

Somewhat over a year ago, Mr. West then assistant general manager and now general manager of the Central Colorado Power Co. made a careful series of high-voltage line loss, wave-distortion and charging-current tests. He gave the writer copies of the results of these tests at the time they were obtained because of the wish on the part of the latter to make a study of the fundamental principles of their highly interesting characteristics. Mr. West has consented to the publication of the data referred to above in the following charts:

The Shoshone station voltage wave form is excellent, being nearly sinusoidal.

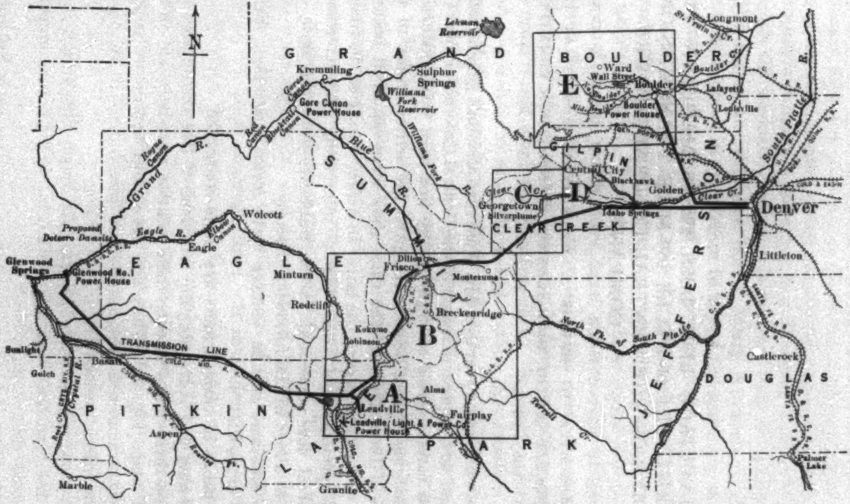
All banks of transformers are delta-connected.

The sizes and corresponding locations of line conductors are given on their charts whence their location may be made on the profile map, Fig. 2. They are six-strand hemp-core copper conductors mounted horizontally, in line, outers 10 ft. 4½ in. (3.15 m.) from the center.

Tower spacings average 750 ft. (228 m.). Suspension insulators disk type, four disks 10½ in. (26 cm.) in diameter connected with solid copper links.

In a letter to the writer dated September 14, 1910, Mr. West says: " I spent a great deal of my time in the generating stations when the line was put into operation and I took the ob-

MAIN TRANSMISSION LINES OF CENTRAL COLORADO POWER CO.


N
GRAND
BOULDER
GILPIN
CLEAR CREEK
JEFFERSON
DOUGLAS
EAGLE
SUMMIT
LAKE
PARK
PITKIN
A
B
C
D
E
Lehman Reservoir
Kremmling
Sulphur Springs
Gore Canon
Gore Canon Power House
Williams Fork Reservoir
Williams Fork R.
Blue R.
Red Canon
Blacktail Canon
Grand R.
Rayne Canon
Ward
Wall Street
Boulder
Boulder Power House
Longmont
St. Vrain Cr.
Boulder Cr.
Lafayette
Louisville
South Platte R.
Central City
Blackhawk
Golden
Clear Cr.
Georgetown
Silverplume
Idaho Springs
Denver
Littleton
Castlerock
Palmer Lake
Proposed Dotsero Damsite
Eagle R.
Eagle
Wolcott
Glenwood Springs
Glenwood No. 1 Power House
Minturn
Redcliff
Dillon
Frisco
Montezuma
Breckenridge
Kokomo
Robinson
North Fk. of South Platte
Terrell Cr.
Alma
Fairplay
Leadville
Leadville Light & Power Co. Power House
Granite
TRANSMISSION LINE
Sunlight
Gulch
Basalt
Crystal R.
Aspen
Roaring Fk.
Marble

Lines extend from Shoshone Power House near Glenwood Springs to Denver, 153 miles
The main transmission lines of the Boulder Project, 29 miles long, are also shown
FIG. 1

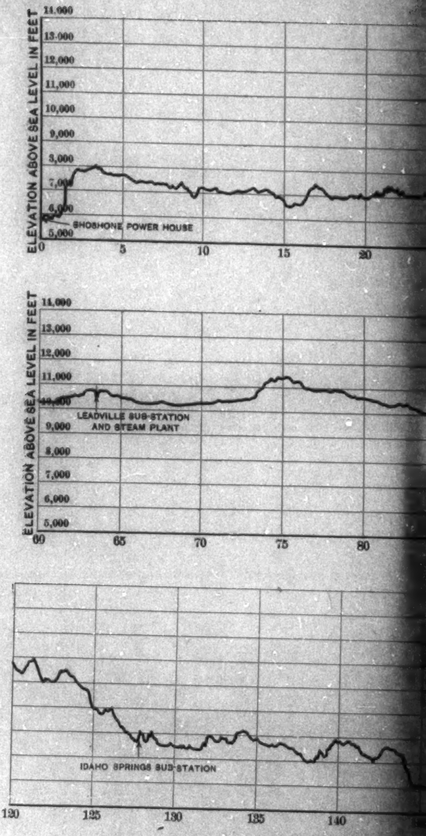
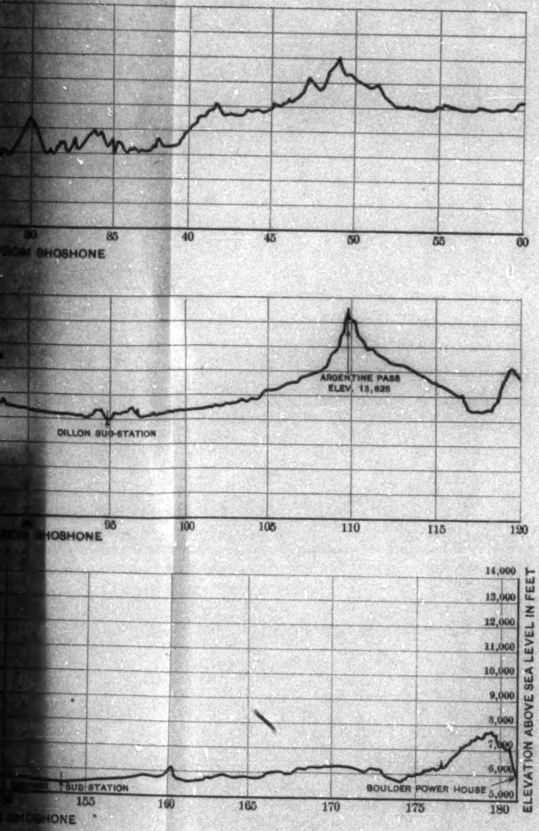


FIG. 2.—Profile of transmis



Shoshone to Denver-Denver to Boulder

[West p. 78]

servations myself and used every means possible to secure accuracy. When the rheostat load tests were made I stationed the operators, who had previously been trained to obtain accurate observations, at the Shoshone or generating end of the line, while I conducted the test from the Boulder or load end of the line. In order to get simultaneous readings I signaled the telegraph operator at Shoshone over our telegraph line by repeating the letter R at intervals of about five seconds. The observers at Shoshone could hear the telegraph instrument so in this manner we obtained simultaneous readings at both ends of the line. In addition to this we had curve-drawing instruments for voltage and kilowatts at both ends of the line and all instruments were calibrated carefully before and after the test. After the observations were taken I compared the curve-drawing instrument charts and in this way was able to eliminate any errors of observation, so that I believe the data obtained are nearly as reliable as a test conducted in a laboratory where all instruments would be located at one point."

Again in a letter dated August 11, 1910, Mr. West writes:

"As I understand it, the specific question you would like answered is whether the difference in results shown by tests No. 7 made on July 23, and tests No. 10 made on November 14 can be explained by difference in atmospheric conditions. Both Mr. Charles S. Ruffner, our operating superintendent, and I do not think this difference is due to weather conditions, but believe that it is due to different connections of transformers to the line. You will note in test No. 7 that transformers were connected at Leadville, Dillon and Denver, and there were 30 miles (48 km.) on the end of the line from Denver to Boulder which had nothing connected to them; *i.e.*, during this test there were no transformers connected at Boulder where the line voltage was highest, whereas, during tests No. 10, transformers were connected at Denver and Boulder only, with no other intermediate connections from Denver to the generating station.

"From here on I will let Mr. Ruffner dictate:

"We believe that the differences in load shown on the same length of line may obtain under different conditions of transformer connections, being particularly affected by the location of such transformers.

"On this particular system the connection of transformers (while adding small losses in the transformers themselves) decreases the total loss, by reason of local non-uniform reduction

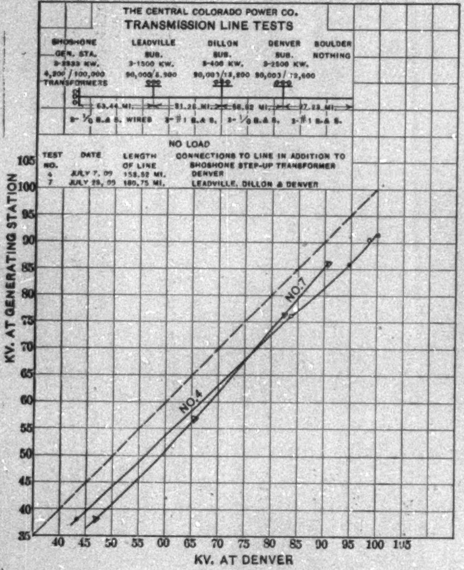

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA. 3-2333 KW. 4,200/100,000 TRANSFORMERS
LEADVILLE SUB. 3-1500 KW. 90,000/6,900
DILLON SUB. 3-400 KW. 90,000/13,200
DENVER SUB. 3-2500 KW. 90,000/12,600
BOULDER NOTHING
63.44 MI.
31.26 MI.
56.02 MI.
27.23 MI.
3-1/0 B.&S. WIRES
3-#1 B.&S.
3-1/0 B.&S.
3-#1 B.&S.
NO LOAD
TEST NO.
DATE
LENGTH OF LINE
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMER
4 JULY 7, 09 153.52 MI. DENVER
7 JULY 28, 09 180.75 MI. LEADVILLE, DILLON & DENVER
NO.7
NO.4
KV. AT GENERATING STATION
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
KV. AT DENVER
40
45
50
55
60
65
70
75
80
85
90
95
100
105

Fig. 3

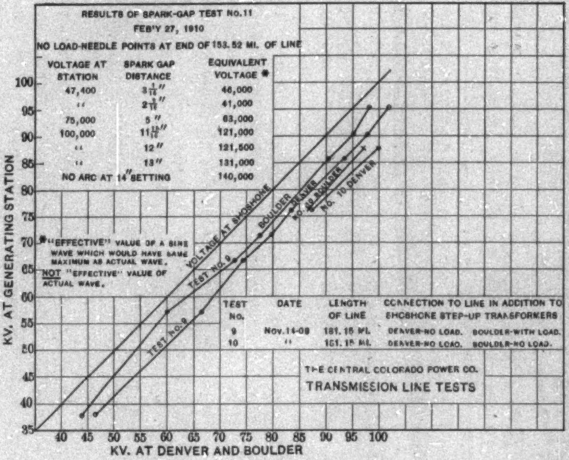

RESULTS OF SPARK-GAP TEST No.11
FEB'Y 27, 1910
NO LOAD-NEEDLE POINTS AT END OF 153.52 MI. OF LINE
VOLTAGE AT STATION
SPARK GAP DISTANCE
EQUIVALENT VOLTAGE *
47,400 3 1/16" 46,000
" 2 9/16" 41,000
75,000 5" 63,000
100,000 11 13/16" 121,000
" 12" 121,500
" 13" 131,000
NO ARC AT 14" SETTING 140,000
* "EFFECTIVE" VALUE OF A SINE WAVE WHICH WOULD HAVE SAME MAXIMUM AS ACTUAL WAVE.
NOT "EFFECTIVE" VALUE OF ACTUAL WAVE.
VOLTAGE AT SHOSHONE
TEST NO. 9
TEST NO. 9
BOULDER
DENVER
NO. 10 BOULDER
NO. 10 DENVER
TEST NO.
DATE
LENGTH OF LINE
CONNECTION TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
9 Nov.14-08 181.15 MI. DENVER-NO LOAD. BOULDER-WITH LOAD.
10 " 181.15 MI. DENVER-NO LOAD. BOULDER-NO LOAD.
THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
KV. AT GENERATING STATION
35
40
45
50
55
60
65
70
75
80
85
90
95
100
KV. AT DENVER AND BOULDER
40
45
50
55
60
65
70
75
80
85
90
95
100

Fig. 4

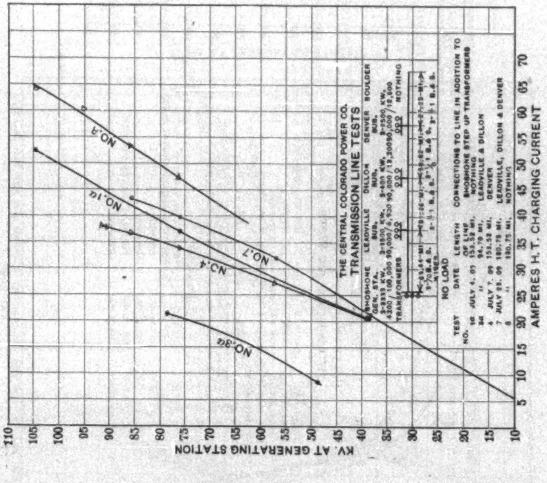
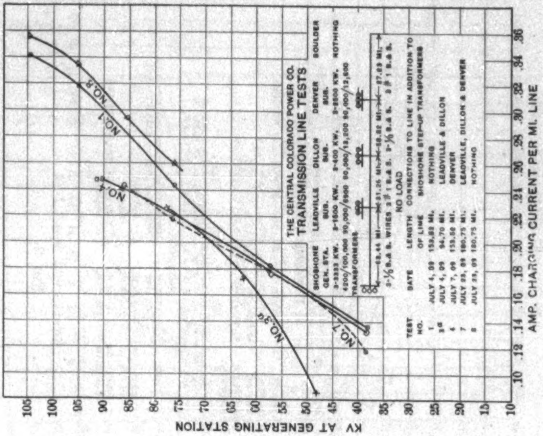

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA.
LEADVILLE SUB.
DILLON SUB.
DENVER SUB.
BOULDER
NOTHING
NO LOAD
TEST NO.
DATE
LENGTH OF LINE
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP UP TRANSFORMERS
NO. 8
NO. 1a
NO. 7
NO. 4
NO. 3a
KV. AT GENERATING STATION
AMPERES H. T. CHARGING CURRENT
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
10
15
20
25
30
35
40
45
50
55
60
65
70

FIG. 5


THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA.
LEADVILLE SUB.
DILLON SUB.
DENVER SUB.
BOULDER
NOTHING
NO LOAD
TEST NO.
DATE
LENGTH OF LINE
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
NOTHING
LEADVILLE & DILLON
DENVER
LEADVILLE, DILLON & DENVER
NOTHING
NO. 8
NO. 1
NO. 4
NO. 3a
NO. 7
KV AT GENERATING STATION
AMP. CHARGING CURRENT PER MI. LINE
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
.10
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.28
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.32
.34
.36

FIG. 6

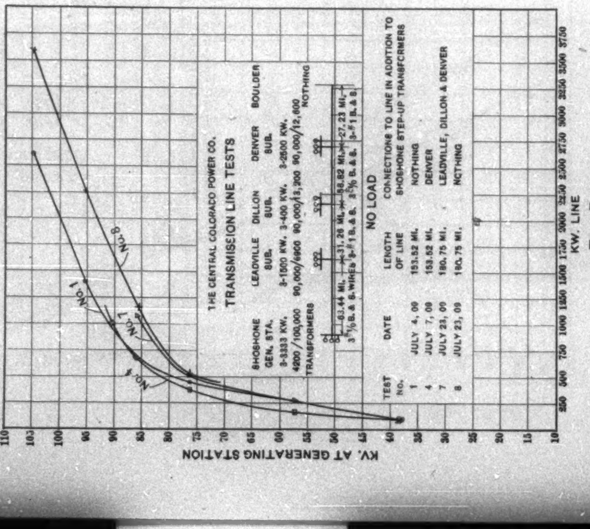
THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA. 3-3333 KW. 4200/100,000 TRANSFORMERS
LEADVILLE SUB. 3-1500 KW. 90,000/6900
DILLON SUB. 3-400 KW. 90,000/13,200
DENVER SUB. 3-2500 KW. 90,000/12,600
BOULDER NOTHING
63.44 MI. 3-⁰⁄₀ B.&S. WIRES
31.26 MI. 3-#1 B.&S.
58.82 MI. 3-⁰⁄₀ B.&S.
27.23 MI. 3-#1 B.&S.
NO LOAD
TEST NO. DATE LENGTH OF LINE CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
1 JULY 4, 09 153.52 MI. NOTHING
4 JULY 7, 09 153.52 MI. DENVER
7 JULY 23, 09 180.75 MI. LEADVILLE, DILLON & DENVER
8 JULY 23, 09 180.75 MI. NOTHING
No. 1
No. 4
No. 7
No. 8
KV. AT GENERATING STATION
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110
KW. LINE
250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3500 3750

FIG. 7

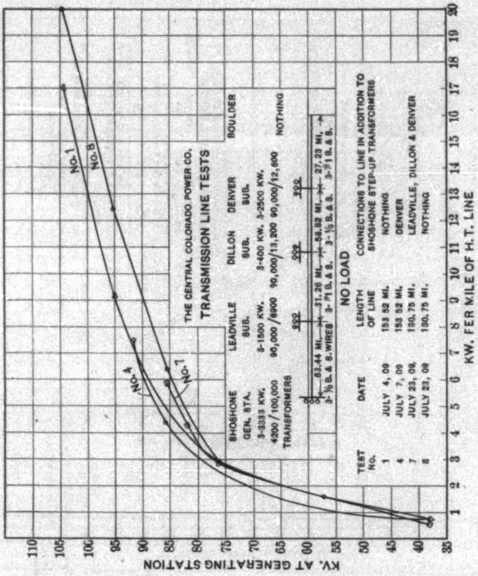
THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA. 3-3333 KW. 4200/100,000 TRANSFORMERS
LEADVILLE SUB. 3-1500 KW. 90,000/6900
DILLON SUB. 3-400 KW. 90,000/13,200
DENVER SUB. 3-2500 KW. 90,000/12,600
BOULDER NOTHING
63.44 MI. 3-⁰⁄₀ B.&S. WIRES
31.26 MI. 3-#1 B.&S.
58.82 MI. 3-⁰⁄₀ B.&S.
27.23 MI. 3-#1 B.&S.
NO LOAD
TEST NO. DATE LENGTH OF LINE CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
1 JULY 4, 09 153.52 MI. NOTHING
4 JULY 7, 09 153.52 MI. DENVER
7 JULY 23, 09 180.75 MI. LEADVILLE, DILLON & DENVER
8 JULY 23, 09 180.75 MI. NOTHING
No. 1
No. 8
No. 4
No. 7
KV. AT GENERATING STATION
35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110
KW. PER MILE OF H.T. LINE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

FIG. 8

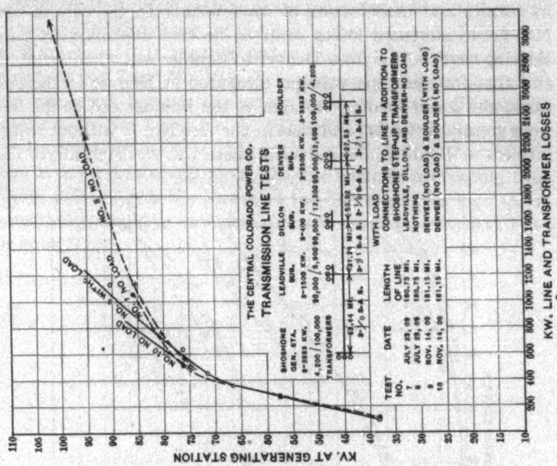
THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA.
LEADVILLE SUB.
DILLON SUB.
DENVER SUB.
BOULDER
TRANSFORMERS
TEST NO.
DATE
LENGTH OF LINE
WITH LOAD
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
7 JULY 23, 09 180.75 MI. LEADVILLE, DILLON, AND DENVER-NO LOAD
8 JULY 23, 09 180.75 MI. NOTHING
9 NOV. 14, 09 181.15 MI. DENVER (NO LOAD) & BOULDER (WITH LOAD)
10 NOV. 14, 09 181.15 MI. DENVER (NO LOAD) & BOULDER (NO LOAD)
NO. 8 NO LOAD
NO. 7 NO LOAD
NO. 9 WITH LOAD
NO. 10 NO LOAD
KW. LINE AND TRANSFORMER LOSSES
KV. AT GENERATING STATION

FIG. 10

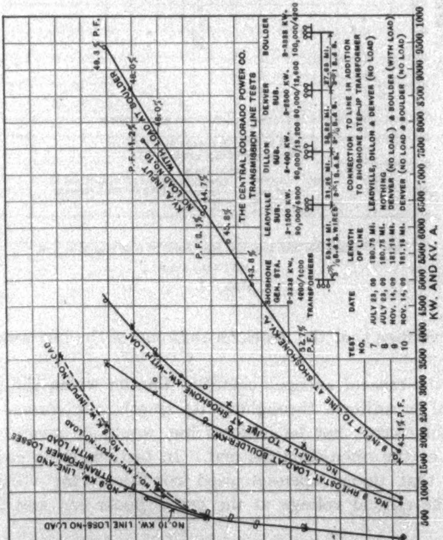
THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA.
LEADVILLE SUB.
DILLON SUB.
DENVER SUB.
BOULDER
TRANSFORMERS
TEST NO.
DATE
LENGTH OF LINE
CONNECTION TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMER
7 JULY 23, 09 180.75 MI. LEADVILLE, DILLON & DENVER (NO LOAD)
8 JULY 23, 09 180.75 MI. NOTHING
9 NOV. 14, 09 181.15 MI. DENVER (NO LOAD) & BOULDER (WITH LOAD)
10 NOV. 14, 09 181.15 MI. DENVER (NO LOAD & BOULDER (NO LOAD)
49.3% P.F.
KV.A. INPUT NO. 10 NO LOAD
P.F. 11.2%
LOAD AT BOULDER WITH LOAD
NO. 9 INPUT TO LINE AT SHOSHONE-KV.-A.
NO. 9 SHOSHONE KW.-WITH LOAD
NO. 9 INPUT TO LINE AT SHOSHONE-KW.
NO. 9 RHEOSTAT LOAD AT BOULDER-KW.
NO. 8 KW. INPUT-NO LOAD
NO. 7 KW. INPUT-NO LOAD
NO. 9 KW. LINE AND TRANSFORMER LOSSES WITH LOAD
NO. 10 KW. LINE LOSS-NO LOAD
42.1% P.F.
KW. AND KV. A.
KV. AT GENERATING STATION

FIG. 9

in voltage and modification of wave form. In the case of test No. 7 the increased losses seem to be best explained by considering that the line from Denver to Boulder was open-circuited, and that for the same voltages measured at Denver in the two cases, the corresponding voltages at the Boulder end of the line were greatly different; and that in the test No. 7, without transformers at Boulder, the potential there was so much above the critical voltage that the losses on that end of the line were very high.

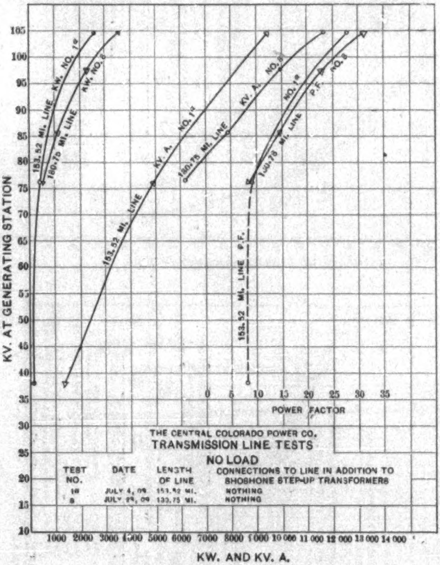

FIG. 11

"In the case of an open-circuited line on which the rise in potential is uniform throughout its length, the corona losses would, of course, not be uniform but would be several times greater at the open-circuited end. In fact, in some cases we believe that under open-circuited conditions the voltage is below the critical voltage at the power house end and is very much above the critical voltage at the open circuited end, thereby producing the greater part of the loss at the open end of the line.

"We believe that another factor causing the difference between tests No. 7 and No. 10 is the location at which transformers were connected, because this effect is shown by the differences between tests No. 1 and No. 4. The effect of connecting intermediate transformers is to reduce the voltage below the critical value at several intervals along the line thereby preventing the average voltage over the length of the line raising as high as it undoubtedly would in case transformers were connected at but one point."

DISCUSSION ON "OPEN ATMOSPHERE AND DRY TRANSFORMER OIL AS HIGH-VOLTAGE INSULATORS", NEW YORK, JANUARY 13, 1911.

M. I. Pupin: In this paper we have a treatise on the electron theory in its application to the explanation of phenomena which take place on high potential transmission wires.

I am glad that makes it unnecessary for me to discourse here on the electron theory. I will only say that the engineer who proposes to study the phenomena which accompany high potential transmission, cannot get along at all without this magnificent theory. It is a theory which makes an epoch in the development of electrical science. Professor Ryan has done well to grapple this theory and see whether he could coördinate the very numerous experimental facts which engineers have observed from time to time in connection with high potential transmissions, particularly in connection with this most bothersome phenomenon, corona discharge from wires.

When I was studying in the University of Berlin, there was a doctor there named Knorr, who was investigating the subject of the electrification of perfect gases, and he came to the conclusion that perfect gases cannot be electrified. This means that perfect gases cannot be decomposed by any electrical stress. By perfect gases I mean oxygen or hydrogen or any other ideal gas which is absolutely pure, or as pure as human hands can make it. This fact was known prior to our knowledge of the electron theory, and is admitted to-day.

Another thing which was found prior to the electron theory, was, that if we take two metallic electrodes, and put them in a vessel, and then make as perfect a vacuum as we can with our modern methods of extremely low temperatures, then no electrical tension, no matter how high, between these electrodes, can produce a discharge between them. That means that unless there is some matter between metallic electrodes, electricity cannot be passed from one electrode to another.

Now, if we cannot get any electricity out of a perfect gas by any tension whatsoever, and we cannot get any electricity from metal electrodes without any matter between them, or with a perfect gas between the electrodes, then it seems to be demonstrated that the perfect gas between two metallic electrodes cannot be a vehicle of electricity between these two electrodes, no matter how high the potential. I think the logic of that will be admitted.

If a perfect gas between two clean metallic electrodes cannot convey electricity from one electrode to the other, under the influence of any electrical stress under our disposal, what is going to do it.

Professor Ryan says, and correctly, the ions of electricity that are there. You must have electrons there, free electrons or free ions. He calls that "dirt" in one part of his paper, but it is not to be understood as ordinary dirt. It is the presence or a mixture of some foreign substance which does not belong there, for if we have clean electrodes and a pure gas, anything else that is present, is " dirt " in that sense.

If the dirt were not there, we could not pass an electrical current by any stress because we do not produce the electrical current between the conductors. That current is not produced by the simple breaking down of something under electrical stress. The electrical field takes a free electron and accelerates it, and when a free path in which an electron moves is long enough for the force, the velocity attained by the electron may be sufficient that when it collides with some atom in this space between them, we get more electrons. That is the source of supply—ionization by collision.

The smallest particles, the electrons, produce the ionization by collision because on account of their smallness they will attain the highest velocity under the same accelerating force, the mass being so extremely small.

The ionization power of the moving electrical charge, depends not on the velocity of the particle multiplied by its mass; it depends on the product of its velocity into its electrical mass. If the electrical mass is small, and the gravitational mass is large, the ionization will be small, whereas if the gravitational mass is large, and the electrical mass is small, then the electrokinetic momentum obtained will be very large.

There is one thing I will add to what Professor Ryan has said, and which seems to me to be quite important. That is, the potential is not equally divided over the distance between two electrodes. When the difference of potential between two electrodes of very large length, is 100,000 volts, and the distance between these two electrodes is two inches, it would be wrong to say that for every point between these two electrodes, the force per unit length was 100,000 volts. It is far from true, because it may have been ten times as much close to the electrodes and very much less in the middle of the distance between them. So that in all experimental operations on electrical discharges, we have to be careful when we specify what the potential gradient is at any given point. We must, in order to specify it correctly, or we should know the amount of free electrons that the space between the two electrodes contains. The amount of these free electrons will modify the potential gradient, making it considerably larger nearer the electrodes, and considerably smaller at points distant from the electrodes.

If the two electrodes, however, are very close together—say 1/100th of an inch from each other, then we would get results which are very near correct. All experiments in which the potential gradient was found to be 76 kilovolts were made with the electrodes very close together.

Professor Ryan attaches a great deal of importance to the tendency of the discharge through the gas to form a core.

At the negative electrode there is a uniform discharge, and at the positive electrode when a certain current density is reached, there are then filaments or streamers like a brush discharge. When the potential is raised and the luminosity is increased on the brush we get a beautiful corona, and then a spark, or the formation of an arc. When that occurs, the electricity runs through a single channel and no flow occurs anywhere else.

According to Professor Ryan, and I agree with him, that is caused by the so-called dynamic force between the elements of these currents. In air, under ordinary pressures, the electrodynamic force or attraction is greater than the repulsion.

This paper is a treatise, and nothing else, on the subject of applying the electron theory for the purpose of co-ordinating all our experimentally observed phenomena of electrical discharges from high potential transmission wires. When we consider the kind of a treatise this is, it can easily be seen that the paper is not one that lends itself very much to discussion.

G. Faccioli: Professor Ryan has referred to some experiments which Mr. Moody and myself performed two years ago. I will answer the questions which Professor Ryan has asked in connection with these experiments.

We started our tests by using concentric cylinders, but we found that the edge of the outside cylinder introduced a considerable error in the results. We then adopted the other form of condenser constituted by a small cylinder parallel to a plate.

The results were the same whether both the electrodes were ungrounded or whether one electrode was grounded. Furthermore, if the size of the plate was reduced, the full corona voltage of the rod was not affected. If, however, the plate was entirely removed, then of course, the corona voltage rose to very high values.

I think that the results were not disturbed by the fact that the air had some absolute potential, but our tests, which extended over a period of several months, proved that the bodies in the immediate neighborhood of the electrodes and especially of the small cylinder (where the electrostatic field is most intense) are responsible for the discrepancies between the values obtained by test and the values given by formula.

The suspension and excitation of the rod are the most important elements of disturbance. If the rod is energized from both ends, then corona will start in the middle and spread gradually toward the ends. If, however, the rod is energized from one end only, then corona will start at the free end, and spread toward the excited end, the full corona voltages being different in the two cases. Our tests, were undertaken to study the behavior of apparatus of limited dimensions, and therefore the influence of the rod suspension, etc., was carefully studied and no attempt was made to eliminate it.

The paper by Mr. Moody and myself, shows the behavior of the electrostatic field when a piece of insulating tape is wrapped around the surface of the small cylinder. In this case a brush starts at the edges of the solid insulation at a voltage considerably lower than the voltage necessary to produce full corona on the rod. This phenomenon shows that to the two classes of "dirt" which Professor Ryan has pointed out, a third class should be added, namely, the "dirt" produced by insulating materials on the surface of the conductors. This class of "dirt" is very important, as to this class belong, for instance, the line insulators.

I have seen part-corona formed on high-tension lines at comparatively low voltages in spots where the hemp center of the conductor was projecting between the copper strands.

This phenomenon given by solid insulation wrapped on the surface of the conductor when the dielectric is air, does not occur when oil is used as dielectric. For instance, in one of the examples shown by Professor Ryan, we have a rod ⅛ in. (3.17 mm.) in diameter, 15 in. (38 cm.) long and 6½ in. (16.5 cm.) away from a plate. When the system is in air, then corona starts on the rod, at 45,000 volts. If, however, a piece of insulating tape (specific capacity, 4.5) is tied on the rod, a brush will start at the edge of the tape at 37,000 volts.

Now, if the system is immersed in oil, part-corona starts at 100,000 volts, whether the rod has solid insulation on its surface or not. Even if we use insulating materials of specific capacity far above the specific capacity of oil, this phenomenon, which is so prominent in air, is absent under oil.

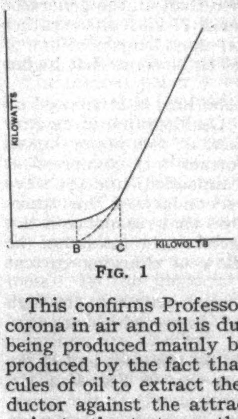

FIG. 1

This confirms Professor Ryan's theory that the formation of corona in air and oil is due to different causes, in the former case being produced mainly by "collision"; in the latter case being produced by the fact that the electrostatic field helps the molecules of oil to extract the electrons from the surface of the conductor against the attraction of the metallic molecules.

As to the tests on the line of the Central Colorado Power Company, I am presenting a paper to the American Institute of Electrical Engineers on this subject, and the paper is published in the January, 1911 PROCEEDINGS. I will, however, discuss rapidly two or three points now. Professor Ryan distinguishes three different stages of corona; First, sub-corona, when losses are present, but no luminous phenomena occur. Second, part-corona when the conductor glows in spots. Third, full corona, when the surface of the conductor is entirely surrounded by corona.

The curve which gives the kilowatts in function of the kilovolts, has three distinct parts: A lower part, an elbow and an upper part. (See Fig. 1.)

I do not think that sub-corona corresponds to the lower part, part-corona to the elbow and full corona to the upper part. In fact, in the case of the Central Colorado Power Company's line, the losses above the critical voltage are represented by a quadratic equation of the form $K\ (E—V)^2$, where K is a constant, E the applied voltage, and V a constant critical voltage.

In this case V is 80 kilovolts, (point B in the figure) and the voltage C at which the upper part of the loss-curve begins, is 107.5 kilovolts.

This means that from 80 to 107.5 kilovolts, the elbow of the curve is composed of two parts; one part given by full-corona losses and the other part given by part-corona losses.

As to the critical voltage of the Central Colorado Power Company's lines, Professor Ryan has deduced the value of 77 kilovolts from curves which give the losses of 150 or 180 miles of lines. In this case the abscissae of the curve are the kilovolts at the generator end of the line. But, the voltage of the far end of the line is considerably higher than at the generator end. It seems, therefore, that the value of 77 kilovolts is rather low. From tests which I have taken on short lengths of line of this system, this critical voltage appears to be somewhat higher than 80 kilovolts.

The rise of voltage at the far end of the line, is attributed by Professor Ryan mainly to resonance. Oscillograms of electromotive force and charging current taken at the power house, give sine waves. A step-down transformer was connected at the far end of the line at Denver (line unloaded) and the wave of the electromotive force across the secondary of this transformer was also a sine wave. This shows that resonance is not a prominent factor and the rise of potential at the far end of the line can be simply explained by the flow of charging current through the inductance of the line.

The curve of losses is so steep in the upper part that the high voltage at the far end explains the high losses which are concentrated at this far end.

In connection with the rise of potential at the open end of the line, I wish to call attention to the fact that in Fig. 4 of Mr. West's communication the voltages corresponding to the spark-gap distances are taken from the standard curve of the American Institute, which is correct at sea-level.

The tests, however, were taken at Denver, which is a mile (1.6 km.) high, and therefore, the actual voltages represented by the sparking distances are lower.

I have taken some tests with spark-gap at Leadville, Colorado, which is 10,500 ft. (3200 m.) high, and by interpolating between the standard curve and the curve obtained at Leadville, I obtain for a 14-in. (35.56 cm.) gap a striking voltage of 115,000 volts instead of 131,000.

Professor Ryan's paper covers such a vast field, from the theory of composition of matter to the most practical problems of line design, that I agree with Dr. Pupin that the best way of discussing the paper is to contribute experimental data. It is immaterial after all whether the electron theory represents absolute truth or not. I welcome this theory which allows the engineer to get a physical picture of the phenomena involved in the disruption of dielectrics.

Mr. Moody and myself have planned to continue our experiments, and have at our disposal 750,000 volts which will allow us to magnify the phenomena, and with Professor Ryan's coöperation we hope to prove the beautiful theories which have been disclosed in this classical paper to-night.

C. P. Steinmetz: I consider Professor Ryan's paper as a continuation of his classic of 1904. In his previous paper Professor Ryan reviewed and analyzed our knowledge of the behavior of air at high voltages, and produced a theoretical formalism representing these phenomena, which has been the basis of all investigations made since that time on the atmosphere at high voltages. His present paper is a continuation of this; and herein I find its great value; in the correlation of the vast amount of experience which has been collected since his 1904 paper, and in the general results derived therefrom.

The present paper is written in the language of the ionization theory, but this I consider merely as an incident and not an advantage, but from my point of view, rather as a disadvantage. In spite of frequent serious endeavors, I have not been converted to the ionization theory, and believe that the theory is not such as to appeal to the engineer, as engineers have to deal with the relations of energy and power, and any speculation on the ultimate condition of matter cannot appeal to us as strongly as to the speculative philosopher or the physicist. Furthermore, as engineers, we must be more careful in the selection of our tools. To the physicist a brilliant theory may appeal. The engineer, however, is confronted with the serious disadvantage in using hypotheses, that usually after a few months all his calculations are checked by the experience with the completed structure, whether transmission line, engine or apparatus, and if the theory was wrong, disaster overtakes the work and the reputation of the engineer. Therefore he must be more careful than the physicist, in whose calculation an error usually is not so serious, as the paper containing it may be withdrawn and corrected, and no harm is done. It is just in this feature that I found the ionization theory to fail. I have never been able to predetermine anything by this theory that I could not predetermine with far more confidence and correctness without this theory. But I have seen predeterminations which were not verified afterwards; although I must say that in every instance afterwards it was found that the ionization theory could be modified to fit the experience. But that is not satisfactory to the engineer, and therefore I do not have much use for the ionization theory.

Coming now to the valuable paper of Professor Ryan, it is not possible to discuss it in its correlation and analysis of facts but it must be studied and digested, and I can only refer to a very few points.

The first of these is the final demolition of the theory of the layer of condensed air which I once was guilty of proposing, many years ago. That was a physical speculation, however. Professor Ryan now brings conclusive evidence corroborating the statement which I made in a discussion a few months ago on the nature of the appearance of the corona: Visual corona appears, not when the voltage gradient has exceeded the critical value at some point in space, but when the range of space where the critical voltage is exceeded, has reached a finite value; that is, to form a corona, it is not merely necessary to have a sufficient voltage gradient, but a sufficient distance covered by this voltage gradient. That is, not only voltage gradient, but voltage or energy is required. That explains the anomaly that the gradient at the conductor when the current begins to be visible, varies with the diameter. It is not the gradient at the conductor, which is determining, but the gradient over a finite distance; and this finite distance is a function of the diameter, which has not been evaluated as yet.

The second interesting feature is the discussion of the coring effect of the current, as explained by Professor Ryan by the magneto-mechanical force. Another explanation I suggested some time ago in the discussion of a paper here, namely, that this coring up is the result of the electrical nature of the conductor —of the air. When you have a uniform conductor exposed to a uniform potential difference, the current density in this conductor may be uniform; but not necessarily so. Under certain conditions in a uniform conductor at uniform potential differences, uniform current density is unstable; and stable condition is concentration of the current into one or a few narrow channels. This condition occurs when the resistivity of the conductor decreases with increasing current density, at a rate greater than the increase of current.

There are many conductors of this character, including solid conductors which can easily be studied. For instance ordinary anthracite coal: Place a lump of anthracite between parallel plates and increase the voltage, and you will find, no matter how uniform you try to get the lump of anthracite, the current density is not uniform, but finally concentrates in a luminous streak. The condition where uniform current density is unstable may be expressed by the equation:

$$-\frac{d\,r}{r} > \frac{d\,i}{i}$$

where r is the resistivity of the conductor and i the current density. In this case the current will core. All gas and vapors, as conductors fulfill this condition. We cannot get in them a uniform current density at uniform potential difference.

The next important point of the paper is the statement that air does not have a definite break-down strength, but that it varies with the conductivity of the air. It appears to me from the data of the paper, that no matter what the natural conductivity of the air is—how many or few ions it contains—there should be a definite break-down strength, or a definite potential gradient where corona begins; but with the limitation that there must not only be a sufficiently high potential gradient, but sufficient distance over which this exists to have the voltage to produce conductivity, or distance to produce sufficient ionization by collision. To use the language of the ionic theory: if we have a voltage gradient sufficiently high to bring the velocity of the electron to ionization by collision, then it is immaterial how many or how few ions you have; it is only a question of the distance. The only condition is to have a few ions in the air, have some trace of conductivity and at some definite potential gradient you must get a break-down. But, the time may vary. That is, I can see that the time element of disruptive strength may be a function of the number of free ions, or the conductivity of the air, but I cannot see how the voltage gradient can be a function.

The last point is this mysterious upper limit of final break-down—the 1,000 kilovolts per centimeter, where, irrespective of the absence of ions, a disruptive discharge takes place. What is the meaning of this? It is explained that free ions are produced from the terminals.

We have two forms of conduction of vapors and gases; one is the conduction of the Geissler tube and the electrostatic spark. Professor Ryan shows how these two phenomena, the disruptive spark and the Geissler tube discharge, are identically the same, differing only according to the gas pressure. That is entirely in agreement with the conception I always had. In this kind of conduction, the current is carried by the material which fills the space between the electrodes. That is, the gas ionizes and so becomes a conductor.

There is, however, a second form of conduction, namely, arc conduction, in which the conductor is a vapor stream of electrode material, connecting the two electrodes. There the material which fills the space does not carry the current, but is immaterial and may be absent.

So, you see the second critical voltage of 1,000 kilovolts per centimeter (using the upper limit) represents that electrostatic stress where spontaneous arc conduction begins; that is, conduction by the material of the electrodes, as conducting vapor stream. Whether electrons are expelled from the terminals or the vapor stream is produced by the electrostatic stress, the physicist may speculate; the engineer sees through the spectroscope that electrode vapor passes between the terminals as conductor of the current, and whether the electrode vapor itself is the conductor, or the ions which permeate it, is of secondary importance. This second critical value thus is the starting point of spontaneous arc conduction. If there is no material in space, that is, an absolute vacuum, at this potential gradient conduction occurs by the conductor issuing from the terminals, so that these 1,000 kilovolts per centimeter would be the disruptive strength of empty space or vacuum. There may be some experimental study for determining the disruptive strength of vacuum.

William Stanley: The corona produced by ionization, the study of which we might well take many evenings to enjoy, is a subject of vast importance. I shall not attempt to add to what the other speakers have said more than to perhaps point out that if the ionization theory is useful and applicable to gases, it should be (mechanically) applicable also to solids. The behavior of the ions within a conductor must bear some simple relation to their behavior outside of conductors, and if Professor Ryan is correct in his assumption that at a voltage of 2300 kilovolts, you can extract pieces of electricity from matter and shoot them off, it is a grave question whether or not you have not then changed the nature of the matter. There is no experimental evidence on this point, nor can I add any; but I have my doubts about the 2300-kilovolt effect. I doubt if it is possible to shoot out of solid material, free electricity without letting some of the matter go with it. I think within the next year we may expect from the engineer, mathematician and the physicist so much more light on the entire subject that the differences of opinion, as to correctness of the theory expressed to-night, will pass away.

There are three different methods of losing energy into air, by convection, by corona and by voltages below corona. I take it that the physicist's theory says that energy is lost by convection when the molecules of the air are charged, repelled and dissipated at slow velocities.

The electric current is a phenomenon due to the movement of negative corpuscles. If a negative corpuscle is sent through gas fast enough, by any means, the phenomena which look like corona will appear. The force which drives a corpuscle at this high speed (electrical speed) is the electrostatic force. The fact that corona is produced by corpuscles shot from a conductor does not matter. If the material discharged consisted of pieces of copper, sent out with the same speed (as corpuscles are sent) we would get the same phenomenon of light (corona).

I have not had time to sufficiently study the paper to permit me to confirm or contradict it, but it is a delightful one and I hope you will have many more of this kind from the same author.

J. B. Whitehead: If I have understood this paper correctly the author considers that corona formation is due to three causes:

1. Spark discharge between the conductor and the neighboring air rendered conducting by diffusion of ions from the opposite conductor.

2. The impact of positive ions on the negative conductor resulting in the giving off of more ions into the air.

3. Ionization by collision between molecules of the air and ions arising as in (2) or from other sources.

I am unable to determine whether the author considers that any one of these causes is sufficient, or that they are coincident, or all parts of one sequence. The experiment of concentric cylinders with short radial separation cited by the author in proof of cause 1 is not conclusive, for under the conditions of the experiment corona and spark voltages are identical and no difference is to be expected; corona cannot be formed under the conditions given. It may be shown that the electric intensities of spark discharge are of a higher order of magnitude than those at which corona start.

Professor Ryan does not give conclusive evidence that impact of positive ions on an electrode may liberate other ions. The cathode ray tube of extremely low pressure may not be relied upon for explanations of phenomena at atmospheric pressure as Professor Ryan, when discussing other matters, has pointed out. A cause for corona of this nature would lead us to expect a difference in corona voltages for different materials of the electrodes, which, however, is contrary to experience. Further, it has been shown in several ways that the electric intensity required to liberate ions from the body of a metallic electrode is of a much higher order of magnitude than that at which air at atmospheric pressures will be ruptured either in the form of corona or spark.

Those who have read my paper, " The Electric Strength of Air " (PROCEEDINGS A. I. E. E., July 1910, p. 1059) will recall that I have suggested secondary ionization, or ionization by collision, as a sufficient cause for corona formation. It is not however necessary to invoke the conductor as a source of the first ions. There are always a sufficient number of free ions in the atmosphere whether indoors or out, inside or outside of tubes, to start ionization by collision. The number of ions under these different circumstances may be quite different at different times, but the vital factor in starting ionization by collision is the electric intensity which must be sufficiently high to accelerate the charged ion to a velocity necessary to ionize the molecule when it collides with it. A greater or less number of the free ions whether due to radioactive emanation, water falls, or other cause does not affect the voltage or intensity at which corona starts.

The author's experiment with two No. 12 wires and one No. 30 wire in between them, the latter excited from an induction machine, does not appear to me to prove the influence of the presence of ions in lowering corona voltage. With the No. 30

wire at a negative potential, since the two No. 12 wires are at alternate positive and negative potentials, the difference in potential between the No. 30 and one of the No. 12's will always be greater than half the difference of potential between the two No. 12s. Consequently corona on the No. 12s would start at a lower voltage when the No. 30 is excited than when it is not. Thus the apparently continuous corona on the No. 12s in the case cited would probably be found to exist on the positive half-waves only. The cessation of the corona on the No. 30 when the alternating voltage is applied to the No. 12's is due to the fact that its initial high value of negative potential is considerably lowered when it is brought into the neutral plane of zero potential due to the two No. 12's, subjected to a difference of potential several times that applied to the No. 30.

That the presence of a greater or less number of ions has no influence on the voltage at which corona starts is evidenced by the fact that corona with descending voltages ceases at the value at which it begins as shown in my paper referred to above. This is true for the actual measured voltage at which corona begins, and also for the values at which it starts and ends on the voltage wave when the voltage is well above the corona starting value. But I have recently performed a very conclusive experiment on this point: The region around a discharging wire was subjected to a copious supply of Roentgen rays, one of the most powerful ionizing agents which may be found, and in this instance causing the discharge of a crude laboratory electroscope at great distance. Absolutely no difference in the voltage at which corona started was caused by subjecting the discharging wire to this influence.

It is a pleasure to note Professor Ryan's adherence to the ionization theory as the means by which we may hope to arrive at a satisfactory solution of these difficult questions. Engineers and engineering schools can no longer afford to disregard the important instrument which this theory offers. High voltage problems are too near to the undiscovered country for the engineer to brush aside the helping hand the physicist is offering him. It is a poor commentary on our Institute if a laboratory worker is belittled or put on the defensive. Careful research, in which conditions are controlled and admitted one by one, have been proven time and time again to be the only means by which a final understanding and economic handling of these and similar phenomena may be reached.

Erich Hausmann: The only limitation at present to increased voltages on aerial energy-transmission circuits is offered by the electric strength of air. The former limitation, imposed by insulation difficulties in high-voltage transformers and in the line itself, no longer exists; for 250,000-volt transformers of large capacity are now available, and the introduction of suspension-type insulators of several units insures good line insulation under extreme weather conditions, the number of such units increasing with the operating voltage.

The critical voltage at which power loss begins through the atmosphere between two clean power-transmission conductors of D inches diameter and spaced d inches apart interaxially has been expressed by the writer[1] by the following empirical equation which embodies the researches of Ryan,[2] Whitehead[3] and Watson[4]:

$$E_m = 47.8\, D^{0 \cdot 8} \log_\epsilon \frac{d}{D} \text{ kilovolts} \tag{1}$$

at 20 degrees centigrade and 760 mm. pressure, for wire sizes between No. 16 and No. 0000; where E_m is the maximum value of the voltage on a representative single-wire perfectly conducting earth-return circuit, or voltage to neutral. The critical voltage for conductors of given size and spacing is practically independent of conductor material, and also of the velocity and humidity of the air. As might be expected according to the electron theory, this critical voltage varies almost exactly with the density of the air. Thus, to render equation (**1**) applicable to lines under all atmospheric conditions, the following factor must be inserted therein:

$$\delta = \frac{p}{760} \cdot \frac{273+20}{273+t} = \frac{0.385\, p}{273+t}, \tag{2}$$

where p is the pressure in mm. of mercury and t is the temperature in degrees centigrade. Consequently in higher altitudes and at high temperatures the critical voltage will be lower.

The foregoing expressions dictate the separation of aerial conductors for a given operating voltage, the size of wire being determined by the energy transmitted and from economic considerations. Let the numerical constant of equation (**1**), the atmospheric density, the crest factor (or ratio of maximum voltage to effective value), the extension factor for multiphase circuits, and the factor of safety (or ratio of critical voltage to impressed voltage), be embodied in a single coefficient K. Then solving the expression for d, there results the necessary separation between conductors for the avoidance of corona as

$$d = \frac{D}{12}\, \epsilon^{\frac{E}{K\, D^{0 \cdot 8}}}$$

or

$$d = \frac{D}{12}\left(\cosh \frac{E}{K\, D^{0 \cdot 8}} + \sinh \frac{E}{K\, D^{0 \cdot 8}}\right) \text{ feet}, \tag{3}$$

where E is the effective voltage between conductors in kilovolts.

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[1] *Electrical World*, V. 56, p. 1179, 1910.
[2] TRANSACTIONS A. I. E. E., V. 23, p. 101, 1904.
[3] PROCEEDINGS A. I. E. E., V. 29, p. 1059, 1910.
[4] *Electrician*, V. 63, p. 828; 1909; V. 64, p. 707 and 766, 1910.

As an illustration, let it be required to determine the proper distance between No. 0000 stranded conductors (0.53 inch diameter) of a 140,000-volt three-phase transmission line in a locality where the highest temperature is 35 deg. cent. and the lowest atmospheric pressure is 600 mm. Assuming an harmonic impressed electromotive force, and a factor of safety of 1.1, the value of K is

$$K = 47.8\,\frac{0.385\times600}{273+35}\times\frac{1}{\sqrt{2}}\sqrt{3}\times\frac{1}{1.1} = 39.9,$$

and

$$\frac{E}{K\,D^{0.8}} = \frac{140}{39.9\times0.602} = 5.83;$$

consequently the distance between the conductors when triangularly spaced is

$$d = \frac{0.53}{12}\times340.359 = 15.0 \text{ feet.}$$

To realize a larger factor of safety than 1.1 as above, a much greater separation of the line wires is necessary. The influence of the factor of safety upon the corresponding distance between conductors of the line just cited is shown by the curve plotted on semi-logarithm paper in Fig. 1, all other conditions remaining unchanged. As greater separation of the conductors means more expensive towers or individual towers for each line, as well as greater outlay in securing wider right-of-way, it is customary to employ low factors of safety.

It is found by experiment that corona loss is proportional to the square of the excess voltage over the critical value and also to the frequency; thus the loss per mile in watts on a single-wire ground-return circuit is quite closely

$$P = 0.024\,f\,(E_s - E_{cr})^2, \tag{4}$$

where E_s is the voltage (effective value in kilovolts) from conductor to neutral at any point on the line distant s miles from its generator end, and E_{cr} is the effective value of the voltage at which corona appears. This equation is similar to those formulated by Dr. Steinmetz at a recent lecture in Brooklyn. On a single-phase line and on a three-phase line (for corona loss per phase) the factor $(E_s - E_{cr})^2$ is respectively four and three times as large as for a single-wire circuit.

An important consideration arises when the distant end of a transmission line is open-circuited, for then the voltage at every point on the line increases, and the potential over a considerable portion of the circuit exceeds the critical voltage, and consequently a loss of energy ensues. This loss begins at that point where the voltage E_0 is just equal to the critical value E_{cr}, and becomes greater and greater as the far end is approached. It is well-known that the voltage at any point on an open-circuited line of length S miles, at a distance s_0 miles from the generator end, is

$$E_0 = E_g\,(\cosh \gamma\, s_0 - \sinh \gamma\, s_0 \tanh \gamma\, S), \tag{5}$$

where E_g is the effective value of the impressed electromotive force, and $\gamma = \beta + j\,\alpha$; β being the attenuation constant, and

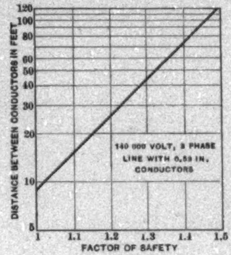

FIG. 1

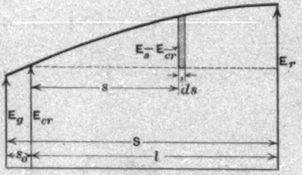

FIG. 2

α the wave-length constant, the values of which in terms of the line constants are:

$$\left.\begin{aligned}\beta &= \sqrt{\tfrac{1}{2}\left[\sqrt{(p^2\,C^2+g^2)\,(R^2+p^2\,L^2)} - p^2\,C\,L + R\,g\right]},\\ &\text{and}\\ \alpha &= \sqrt{\tfrac{1}{2}\left[\sqrt{(p^2\,C^2+g^2)\,(R^2+p^2\,L^2)} + p^2\,C\,L - R\,g\right]}.\end{aligned}\right\} \tag{6}$$

The symbols C, g, L and R are respectively the capacity, leakage conductance, inductance and resistance per mile of line, and $p = 2\,\pi$ times the frequency of the electromotive force. By substituting various values of s_0 in equation (5), and plotting the corresponding values of E_0 in terms of distance, a voltage-distribution curve for the particular line will result. From this voltage-distance curve can be seen the distance from the generator end of the transmission line at which corona begins. Of course, equation (5) might be solved for s_0, but not knowing the phase of voltage E_0 at the end of this part of the circuit, this plan leads to difficulty when applying the resulting expression to the solution of actual problems.

In order to determine the total corona loss on a representative single-wire open-circuited line, consider an element ds of the circuit, distant s miles from the point s_0 where corona begins, for which the excess voltage is $E_s - E_{cr}$ kilovolts; Fig. 2. The power loss over this elementary line section in watts is

$$d\,P = 0.024\,f\,(E_s - E_{cr})^2\,d\,s,$$

and over the entire distance $l = S - s_0$, the loss is

$$P = 0.024\,f \int_0^l (E_s - E_{cr})^2\,d\,s.$$

But from equation (5),

$$E_s = E_{cr}\,(\cosh\gamma\,s - \sinh\gamma\,s\,\tanh\gamma\,l);$$

therefore

$$P = 0.024\,f\,E_{cr}^2 \int_0^l (\cosh\gamma\,s - \sinh\gamma\,s\,\tanh\gamma\,l - 1)^2\,d\,s,$$

or

$$P = 0.024\,f\,E_{cr}^2\Big[\int_0^l \cosh^2\gamma\,s ds - 2\tanh\gamma\,l \int_0^l \sinh\gamma\,s\,\cosh\gamma s\,ds$$

$$+\int_0^l ds - 2\int_0^l \cosh\gamma s\,ds + \tanh^2\gamma\,l \int_0^l \sinh^2\gamma\,s\,ds$$

$$+2\tanh\gamma\,l \int_0^l \sinh\gamma\,s\,ds\Big].$$

Upon integration this equation becomes

$$P = 0.012\frac{f}{\gamma}E_{cr}^2\Big[\sinh\gamma l\cosh\gamma l + \gamma l - \tanh\gamma l(\cosh 2\gamma l - 1) - 4\sinh\gamma l$$

$$+\tanh^2\gamma\,l\,(\sinh\gamma\,l\cosh\gamma\,l - \gamma l) + 4\tanh\gamma\,l\,(\cosh\gamma l - 1) + 2\,\gamma\,l\Big],$$

and when simplified reduces to

$$P = 0.012\,f\,E_{cr}^2\,l\left[3 - \frac{3\tanh\gamma l}{\gamma\,l} - \tanh^2\gamma\,l\right] \qquad (7)$$

as the expression for the total corona loss in watts on an open-circuited single-wire earth-return circuit.

Referring to the 140,000-volt, 10,000-kw., 500-mile, 60-cycle, three-phase transmission line already mentioned, with No. 0000 stranded aluminum conductors placed 15 feet apart, the line constants per mile on a representative single-wire circuit which transmits one third of the total energy, are

R = 0.463 ohm (includes resistance increase due to skin effect and stranding),
L = 0.00218 henry.
C = 0.0137 microfarad.
g is negligibly small = 0.

The attenuation and wave-length constants are respectively

$$\beta = 0.000563,$$

and

$$\alpha = 0.00214.$$

from equations (**6**); whence

$$\gamma = 0.000563+0.00214\,\text{j}.$$

It will be observed that severe conditions are assumed in order to bring out the results more forcibly.

When the line is open circuited at the receiving end, the voltages in terms of the impressed voltage E_g at several points on the line, as determined from equation (**5**), are given in the following table:

Distance from generator (miles)	$\frac{E_0}{E_g}$	$\left\lvert\frac{E_0}{E_g}\right\rvert$
40	1.092 — 0.112j.	1.10
100	1.212 — 0.265j.	1.24
200	1.382 — 0.487j.	1.46
300	1.503 — 0.658j.	1.64
400	1.575 — 0.764j.	1.75
500	1.600 — 0.799j.	1.79

Thus, for a factor of safety of 1.1, the length of line over which corona appears is 460 miles. The total power loss in watts per phase into the air is therefore, from equation (**7**),

$$P=0.012\times 60\times \left(\frac{140\times 1.1}{\sqrt{3}}\right)^2\times 460\times[3-(4.050-1.14\text{j.})$$

$$-(-0.990+1.78\,\text{j.})],$$

or

$$P = 0.72\times \frac{7900}{1000}\times 460\times 0.65 = 1700 \text{ kw.}$$

which is equivalent to a current of $\frac{1700\sqrt{3}}{140}$ or 21 amperes per phase. This current value almost equals the full-load current of $\frac{10{,}000}{140\times 3}$ or 23.8 amperes which would enter this unusually long transmission line. Thus, an ammeter at the power house which supplies energy to this circuit, would indicate approximately the same current when the far end of the transmission line is open-circuited as when connected to the full load, because of the breakdown of the air near the conductors.

Samuel Sheldon: The assumption, made in this paper, that corona is initiated by the extraction of electrons from the cathode as a result of its bombardment by positive ions seems to be based (1) upon the forms of the photographic impressions around the cathode in Figs. 11 to 13, (2) upon the appearance of bright spots at the cathode in the experiments illustrated in Figs. 20 to 24*b*, (3) upon the results obtained by Earhart in 1905, (4) upon the dielectric behavior of gases, at superatmospheric pressures, and (5) upon the generally accepted explanation of the cathode glow in vacuum tubes. An assumption that corona is initiated by electrons set free from gaseous particles in the immediate vicinity of the cathode as a result of collisions with bombarding positive ions is not only consistent with the above conditions but accords with other experimental evidence not easily explained by the cathode electron theory.

The energy required to ionize a gas particle has been determined in a number of ways and is of the order $4.4\ 10^{-11}$ ergs. The energy to set free an electron from aluminum, brass, silver, or platinum cathodes appears, from the results of E. H. Williams,[1] to be greater than this. At any rate the Nipher photographs do not enable one to differentiate as to whether the electrons, flying away from the cathode, came from inside the pin or from gas particles in the immediate vicinity.

The bright luminescent spot experiments, described in the paper, are not adequate to differentiate as to the initial source of electrons. At the pressure used, one-tenth atmospheric, the supply of gas particles in the vicinity of the cathode, although reduced, is yet ample to supply the electrons. The mean free path of a gas particle has been increased by the reduction of pressure, while the viscous retardation at a given velocity and the field intensity necessary to give ionizing energy to the positive ions has been reduced. These factors, however, are of no consequence in this connection.

Earhart's results referred to in the paper and his later results[2] taken together with those of Kinsley[3] and of Hobbs[4] using a spherical electrode and very minute gaps of less than the wave length of sodium light, the latter being accurately measured by means of an interferometer, seemed to point strongly towards a cathode-electron initiation of discharge which entailed the characteristic differences of cathode material but was independent of the nature of the gaseous dielectric. E. H. Williams[5] considered the work of these men as open to two possible sources of error: Either the enormous electrostatic forces exerted at these minute separations pulled the electrodes into contact and thereby occasioned metallic conduction or the path of rupture was longer and different from the shortest path between electrodes. With apparatus of special rigidity he made new determinations and found that the path of discharge was not along the shortest distance, that electrode material had no influence upon the discharge-potential, that ionization of the gas reduced the discharge-potential, that the nature of the discharge for very short distances is the same as for greater distances, and that "*the presence of moisture lowers the discharge potential for very short as well as for greater distances.*" The value derived from Earhart's results, at the bottom of page 29 of the paper, is far too large if the discharge occurred as was the case with Williams—and it would be unsafe to base any conclusions upon the given value.

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[1] *Physical Review*, XXXI, 3, p. 216, 1910.

[2] *Phil. Mag.* (6), 16, p. 48, 1908.

[3] *Phil. Mag.* (6), 9, p. 692, 1905.

The dielectric behavior of gases at superatmospheric pressures is interesting and, if it were not for Fig. 17*b*, might perhaps be easily explained on the basis of initial gas ionization. This figure is not referred to in the text, differs materially in general shape from Fig. 18 although both refer to carbon dioxide, and seems to be based upon Fig. 2 in *The Electric Journal* paper. The individual observations therein given would seem to warrant a drawing of the curve so as to omit the hump which differentiates it from Fig. 18 in this paper. Assume such to be the case. The ionization of a gas particle probably either consists in the withdrawing of an electron from an atom or accompanies gaseous dissociation. If no assisting collision energy were available, it would still be possible to ionize, if the particle were placed in an electric field of sufficient intensity. A very rough estimate of the latter in the case of atom-ionization has been given as 10^9 volts per centimeter. It is possibly dependent upon the valency. The table of insulating values of various gases, quoted from Wolf in *The Electric Journal* article, indicates that the ionizing field intensity increases with change of gas to one succeeding in the following list: hydrogen, oxygen, nitrogen, carbon dioxide. The corresponding molecular bonds are respectively one, two, three and four. If now one of these gases, such as carbon dioxide, be subjected to an increasing field intensity, two ionizing agencies will contribute energy, collision with antecedent ions and opposed ionic displacement in the gas particle. At at-

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4. *Phil. Mag.* (6), 10, p. 617, 1905.

5. *Phys. Rev. Lc.*

mospheric pressure the former is predominant. As the pressure is increased the mean free path is diminished and as a result the critical field intensity is raised. The proportion of the ionizing energy contributed by the second agency is thereby increased. After the pressure has been sufficiently raised the energy of collision becomes a negligible factor and the rupturing voltage remains constant. The curves for air, however, certainly have a hump at a pressure of about 10 atmospheres. But air is a mixture of oxygen and nitrogen with some other gases in small quantities. Furthermore the formation of ozone in comparatively low field intensities and of nitric oxide at higher intensities indicate that the former is due to the dissociation of oxygen and the latter to the subsequent dissociation of nitrogen. A consideration of the possible relations between restraining forces and displacements in the atom and molecule, which is beyond the scope of this discussion, indicates that the initiation of the hump accompanies the initial ionization of the nitrogen of the air.

The explanation offered in the paper for the general shape of these curves, namely a copious emission of electrons from the cathode because of the great transition field intensity, is not in accord with the well-known fact that with very high vacua no emission can be effected with the highest available voltages. The cathode emission in other vacua is the result of bombardment under the combined influences of high field intensities and very long free paths.

H. W. Fisher: Those of us who have heard or read Professor Ryan's former classic papers cannot help but rejoice that he has again presented a paper relative to corona phenomena.

His review and analysis of what others have done is most interesting. His explanation of some of the many strange results relative to sparking distances between needle points, which I presented in my St. Louis Congress paper is a source of satisfaction to me, especially in view of the fact that some of the data then given was called in to question shortly afterwards. Even as far back as 1892 or 1893, I found that with voltages of 1000 or less, the sparking distance increased with the sharpness of the needle points, and that at 6000 volts, the sparking distance could be increased by slightly dulling the points. Thus it seemed evident that the shape of point to produce maximum spark distance would possibly be different for every voltage. My St. Louis paper to a certain extent verified this original idea, but owing to lack of time and facilities for carrying on an elaborate investigation, I was unable to state definitely the form of points which would produce maximum spark distances at different voltages. I was able to show, however, the marked tendency towards a maximum spark distance by employing needles of different point diameters whose points had been measured with a microscope and grating and then assorted and arranged in pairs of like points. Experiments also showed that when points of different diameters were used, the spark distances often depended on the position of the needles in the apparatus.

For instance, under certain conditions, a dull point at the handle side of the apparatus might give a greater spark distance for a certain voltage than would be obtained with the same voltage and the same sized points in reversed positions.

My object in again presenting these facts is two-fold:

1. Because in recent years, I have thought of a plan by which points of almost any small diameter can be constructed, thus making possible a rigid investigation with points decreasing in size to a fraction of a wave length of light.

With a definite and comparatively easy plan of making points of various diameters and in anticipation of an interesting and valuable set of experiments in a line of research work which has only been explored in an elementary manner. I hope someone, who has more time for this kind of study, than is permissible in commercial work, will undertake a rigid investigation of striking distances, and corona effects with both direct and alternating currents.

My plan of constructing points of various minute diameters is to employ the method used by Professor R. A. Fessenden in making the fine wire part of his liquid barretter.

A small platinum wire is first evenly coated by electrolysis with silver to a considerable diameter and then the composite wire is drawn down to a very small size which can result in a possible reduction of the diameter of the platinum wire to the one fifty thousand part of an inch. By the application of a suitable acid to the end of the duplex wire, the silver can be removed and the minute platinum wire made to extend a short distance beyond the composite wire.

By initially starting with a considerable amount of wire, pieces of wire can be cut off at different reductions in area and thus can be secured a great variety of wires of various sizes. With these, experiments can be made showing the results of tests with wires having square ends. Then by the application of a weak solution of aqua regia, the fine platinum points can be rounded off or reduced in size to a fraction of a wave length of light, and thus points of a great variety of forms can be obtained. The examination and the adjusting of these points in the spark distance apparatus would have to be done with a microscope.

Equipped thus with points of a great variety and definite shape and by using generating apparatus giving a steady e.m.f. and unaffected by external conditions, an investigation of this subject could be made which would be most interesting and instructive.

J. E. Noeggerath: It was a good plan on the part of Professor Ryan to adopt the electron theory for his discussion of corona phenomena. For although the theory may be upset some day, as just now some of the most important theoretical considerations in the field of physics are being thrown over—the existence of ether and the permanency of matter and energy—it provides us with an excellent means to corelate facts belonging to different phases of engineering and physics, and thereby to strengthen assumptions that have to be made where sufficient experience does not yet exist.

It is interesting to note how the phenomena in vacuum tubes, upon which Professor Pupin touched, and most important experiments in regard to which were made by Dr. Weintraub, and also other experiments I had the opportunity of conducting, bring out certain facts that are related to corona phenomena, substantiating particularly the following four points:

1. High voltage required to start the ions (conductivity).
2. The continuation of conductivity at voltages lower than the starting voltage.

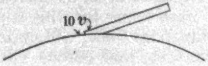

Fig. 2

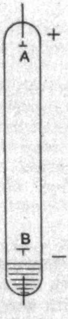

Fig. 1

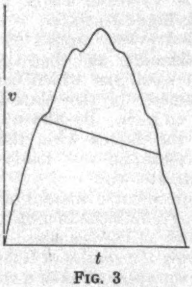

Fig. 3

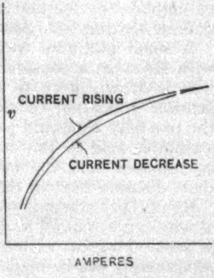

Fig. 4

3. The start of ionization at lower voltages if a supply of ions exists.
4. High stress near electrodes and low voltage gradient between them.

1 and 2. The parallel phenomena in mercury vapor lamps are well known. A simple direct current lamp, like the one shown in Fig. 1, can be started by raising the voltage to a very high value; but the current will continue to flow, if once started, at a very much lower voltage.

The same I found to be true with laminated brushes on collector-rings running up to speeds of 25,000 ft. per min., when the conditions were not favorable (Fig. 2). It took occasionally more than 10 volts to start a current, which in every case continued to flow at a voltage of the magnitude of one volt. There was no visible arc formation when this occurred.

Means for comparing the similarity of the conditions in high tension lines and brush contacts are given in Mr. Whitehead's A.I.E.E. paper of June, 1910, (Fig. 3). It shows how the conductivity through ionization continues at lower voltages once it is started. On raising, in brush contact tests, the current (when new ions have to be produced) the voltage was higher than on lowering the current at the same current density (when a supply of ions already existed) Fig. 4.

3. A good illustration of the start of ionization at lower voltages if other ions are present, is presented by Professor Ryan in Fig. 28. Similarly, if the direct current vapor lamp is connected with a side branch, as shown in Fig. 5, an artificial production of ions can be started by shaking the tube and thereby connecting the mercury in the side branch at *C* and *D*. When the mercury is disrupted again the current continues to flow as in any arc lamp when the carbons are separated, and a stream of ions issues from the cathode. That they move in every direction can be seen from the luminosity issuing from the cathode into the main tube until it reaches the anode. Then the whole column has become a good conductor and the normal current flows.

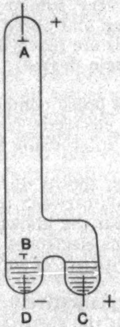

FIG. 5

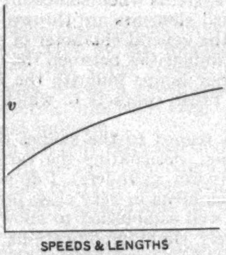

FIG. 6

Similarly, instead of raising the voltage, the contacts mentioned above can be put into operation by increasing the pressure upon the brush and establishing thus momentarily a metallic contact. The current will continue to flow after it has once been started, even after the pressure has been reduced to its original value.

4. The critical striking distance Professor Ryan mentions, or the thin film of high dielectric strength means that there is a high stress near the electrodes and a low voltage gradient in the

space between. The same condition exists in a vapor lamp, (as shown in Figs. 1 and 5) the stress between the points *A* near the anode, and the anode and points *B* near the cathode, and the cathode, being higher than the stress for a similar distance between points in the space between the electrodes. Thereby, it does not make much difference how close the points *A* and *B* are taken from the anode and cathode. The result is that, when the length of the mercury lamp is increased, the voltage required for a given current does not increase in proportion to the length of the tube, due to the constant or practically constant electrode voltages.

Of course such measurements cannot be taken in brush contacts because the space between ring and brush is too small (Fig. 2). However, the curves giving the relation between the voltages and lengths for arcs of a constant cross section (mercury vapor lamps) at a constant current value, are very similar to the curves showing the relation between voltage and speed in collecting systems when sufficiently high speeds are reached (when the brush elements are thrown off to a certain degree). Fig. 6 shows the general character of such curves.

The similarities between the curves of the brush contacts and the vapor lamps indicate the existence of electrode potentials also in brush contacts to which that of the intervening space is added.

With regard to the shapes of the curves, shown during the discussion, designating the various potentials between the electrodes (wires, cylinders), I do not believe that the knowledge of the phenomena in very close proximity to the electrodes is sufficiently well established to allow a proper criticism of such comparatively slight modifications.

I should prefer to express the conditions qualitatively, simply stating that there is high electric stress near the electrodes and low stress in the field between them.

To turn from these theories to practical considerations, all indications, particularly that of the comparatively small influence of the distance between wires (which is a result of the high stresses near the wires and low voltage gradient in the space between) and the effect of the maximum voltage, point to two requirements if in time higher voltages are to be used.

1. A very big increase in the distance between wires. This means earth return, which can be attained, first, by single phase transmission; second, by direct current transmission.

2. The choice of a maximum voltage as close to the effective voltage as possible, which again means direct current transmission.

An exhaustive comparison of the various systems cannot be made in the brief space allowed for this discussion, but I shall mention the most serious objection that will at once be raised; namely, that no reliable high-tension commutator or acyclic generators or motors exist for high tension direct current systems.

However, when it is considered that in a single installation, over $1,000,000 may be saved by using direct current instead of the present form of transmission, it may be worth while to spend some money on development, and in view of the vast amount of ground work done by Mr. Thury in Switzerland, it seems not improbable that high tension direct current transmission may find its field after all.

A. E. Kennelly: This paper of Professor Ryan bids fair to become as important in the literature of corona formation around high-tension conductors as his previous paper of 1904. In his 1904 paper, he showed that, under laboratory conditions, with normal air pressure and temperature, corona was produced over a wire of 4 mm. or more in diameter, when the computed electric intensity in the air reached 30 kilovolts per cm. not just at the surface of the wire, but at a distance of 1.75 mm. (0.07 inch) away from the wire; also, that for small changes of air pressure and temperature, the critical intensity increased directly with the pressure, and inversely as the temperature reckoned from absolute zero.

Since the 1904 paper was read, observations have been reported on actual aerial wires, especially by Mr. Mershon, which observations have gone to show that either corona, or brush, forms around a wire in the open air at a considerably lower (30 to 40 per cent lower) electric intensity then Professor Ryan's laboratory results would indicate.

In this paper, Professor Ryan not only discusses and confirms his earlier experimental results, in the light of modern electronic theories; but he also discusses and offers an explanation for the discrepancies between his laboratory results and the results on actual aerial lines.

He accounts for the fact that the electric intensity at the surface of a very thin wire may apparently reach 200 kilovolts per cm. without developing corona, with the aid of the electronic theory, by the proposition that a certain small radial distance is needed around the wire for electrons to develop destructive velocities at subsequent collision. The evidence for this appears to be very strong. Consequently, the normal critical intensity of 30 kilovolts per cm. is to be looked for, not at the surface of a thin wire, but at such a distance therefrom as will enable the electrons leaving the wire to attain a velocity sufficient to smash off new electrons from neutral air-particles, on collision.

He accounts for the reduction observed in critical voltage on actual overhead lines by a number of conditions that do not ordinarily present themselves in the laboratory; such as irregularities on the wires, free ions in the air, moisture, etc. We may call this the effect of " dirt," the dirt being either in the air, or on the wires. He also shows that before full corona is formed, there will be half-corona, or brush-discharge, with considerable loss of electric energy from the wire. The engineering problem is concerned with avoiding appreciable brush-discharge, and full coronation is, from the engineering standpoint, a mere matter of degree. Between the two influences of dirt, and the partial corona or brush, a reduction factor of 72 per cent is offered by Professor Ryan as an average value to represent the ratio between the critical electric intensity over practical lines, to that found in the laboratory. A number of observations on practical lines are collected in the paper and discussed. From a practical standpoint much importance attaches to the value of this reduction-factor and to the influences which affect it.

It is noteworthy that in Fig. 1*b* of the paper the curve of critical surface-intensity under laboratory conditions, from Professor Ryan's measurements, seems to be a rectangular hyperbola, between the limits of 0.15- and 0.8-in. (0.38 and 2.03 cm.) wire-diameter,. That is, the curve between these limits corresponds to the formula:

$$e'' = 76.24 + 9.94/d'' \text{ kilovolts per inch} \qquad (1)$$

or

$$e = 30.01 + 9.94/d \text{ kilovolts per cm.} \qquad (2)$$

where e'' is the critical electric intensity in inch measure and e its corresponding value in cm. measure at the surface of the wire d'' is the diameter of the wire in inches, d its diameter in cm.

The agreement of this formula with the curve of Fig. 1*b* is shown by the following table:

Diam. wire, inches	0.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8
e'' taken from Fig. 1*b* kv. per in.	139	126	110	102	96	92.5	90.2	88.3
e'' computed by formula (1) kv. per in.	142.5	125.9	109.4	101.1	96.1	92.8	90.4	88.7

For diameters below 0.15-in. (3.8 mm.), the curve departs from the hyperbola, towards a parabola, and, for very small wires, the departure is marked.

Consequently, for wires larger than 4 mm. in diameter, Professor Ryan's laboratory results indicate that we may either express the critical coronation intensity as 76.2 kilovolts per in. (30 kv. per cm.) at a striking distance of 0.07 in. (0.178 cm.) from the surface, or as $76.24 + 9.94/d''$ kilovolts per in. $(30 + 9.94/d)$ kilovolts per cm., at the surface itself. From the standpoint of the electronic theory, the constant intensity at the striking distance seems to be the fundamental conception; but there must be some curious cross-relation to bring about the hyperbolic graphical condition here indicated.

The high-voltage line loss tests appended to the paper are extremely interesting from the engineering standpoint, but not very helpful in elucidating the underlying physical laws of brush loss. The line tested runs at various altitudes, is necessarily subjected to an elevation of voltage at the far end when open circuited, and is too long to serve as a fair test for the action of one variable at a time. The curves of Fig. 11, however, show that the apparent electrostatic capacity of the line wire rises very markedly before the brush loss becomes considerable, and the kilovolt-amperes may thus furnish a valuable practical guide to avoid kilowatt brush loss.

F. W. Peek, Jr.: Corona was first seriously investigated with the use of the visual critical point and sparking point as reference. This is recorded in classical papers by Steinmetz, Ryan, and others. On clean parallel conductors the visual critical point is very definite. Experiments show that the apparent dielectric strength of the air is greater around small conductors than larger conductors. This was first explained by assuming that a thin film of condensed air surrounded conductors. If this were so one would expect a greater rupturing gradient for the air surrounding the very dense metals, than for that surrounding the very light metals. Experiments show that this is not the case. Looking farther; in a paper by Hayden and Steinmetz at the last Annual Convention it was shown that definite energy as well as potential is necessary to rupture insulation. This makes it unnecessary to assume the condensed air film. Professor Ryan has also applied the ionization theory here.

Together with the visual tests it is seen to be important to study the phenomenon by energy measurements. This was early recognized and has been done by many investigators. These energy measurements are difficult to make because of the low power factor and high potential. To get accurate and reliable results, then, it is necessary to make measurements directly on the line, eliminating the transformer losses from consideration. This has been done in some very extensive investigations that we have carried on for the past year. It is impossible to go into detail on the methods and data, in this discussion, as it is hoped to present this soon in an extensive paper. A few points will be considered that have a bearing upon the present discussion.

A line of sufficient length to get good wattmeter readings was erected. The conductors were supported by suspension insulators on metal towers, representing standard transmission practice. An approximate sine wave voltage up to 250,000 was available. If voltage is applied to the line at night so that we can note the luminous effect, and wattmeter readings are taken we see at a certain point very low loss readings, which gradually increase with the increase in voltage; localized streamers and corona soon appear at points. The watt increase is still gradual. Slowly raising the voltage, the *visual critical point* is reached. The effect is striking. Corona suddenly jumps out, as it were, all over the line. The line immediately becomes noisy and the loss increases very rapidly with the increase in voltage. The first localized streamers are caused by "dirt," irregularities, or local ionization as described by Professor Ryan. Plotting volts and watts we have a curve with a rather wide knee. Investigating this curve we find that the power loss above the knee may be represented thus:

$$p = cf\,(e - e_0)^2 \tag{1}$$

where p = watt loss, e = line volts, c is a term varying with capacity, and wave shape, f = frequency. e_0 is the *curve critical voltage*. This voltage is considerably below the *visual critical voltage* for small conductors, and approaches the *visual critical voltage*, for large conductors. If now we subtract p values from the actual experimental values we obtain a residual at the lower voltages. This residual is apparently represented by the probability curve, that is,

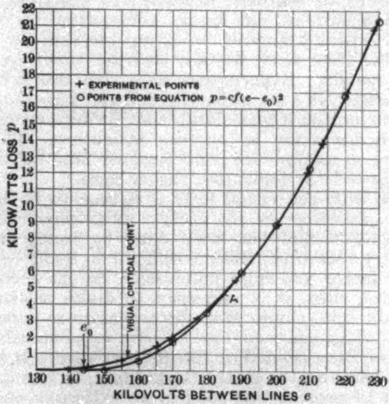

Fig. 1.—Corona loss curve

$$p_1 = d\,\epsilon^{-k(e_0 - e)^2} \tag{2}$$

This expresses the excess loss at the low voltages due to accidental cause, namely, "dirt" spots.

Now if we look at Fig. 1 for a moment the above steps can be followed on the curve. At 140 kilovolts there is a slight loss—localized corona. At 144 kilovolts, e_0, the *curve critical voltage* is reached. Still higher, at 157 kilovolts, we have the *visual critical point*. Fig. 2 shows the line at 200,000 volts.

An interesting point I might note here. Values of $1/e_0$ were taken for a given wire and spacing and plotted against corresponding temperatures. The temperature range was from —13 to 22 deg. cent. The plotted points were in a straight line. This line was extended and cut the temperature axis approximately at —273 deg. cent. Thus absolute zero was determined by corona measurements.

Of important bearing on the ionization theory, and a confirmation of Professor Ryan's view of " vapor products " is the effect of falling rain and snow on e_0. Snow flakes are known to carry considerable charges. Tests made while snow is actually falling show a marked decrease in the voltage at which corona loss starts, and very much greater loss than the corresponding no-snow loss.

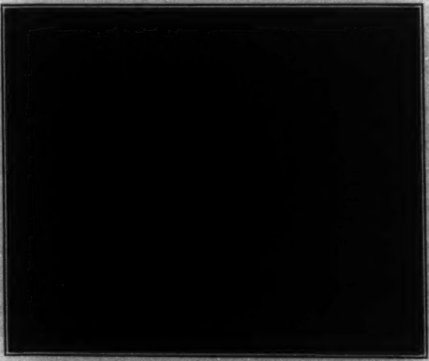

FIG. 2.—Corona on transmission line—No. 3/0 cable, 10-ft. spacing, 200,000 volts

Tests made during one rain storm—a thick misty precipitation —showed a slight, but not serious loss increase. These weather factors should be taken seriously into account in the design of transmission lines. Another effect which has bearing on the theory of Professor Ryan is that of smoke. While one set of tests were being made the wind was in the direction to carry considerable smoke from a factory power house to the line. The losses were greatly increased.

George L. Hoxie: The discussion has developed an apparent wide difference of opinion on the utility of the electron theory. Perhaps this difference of opinion is not so great as it appears. On the one hand there is full recognition of the " epoch making " character, as Dr. Pupin has expressed it, of the electron theory.

On the other hand Dr. Steinmetz refuses to concede the mechanical plausibility of the theory, or its value in predicting physical results. As to the latter time will decide. The former objection, that as a mechanical explanation the theory does not seem plausible, and that in the past the theory has been changed from time to time to fit newly discovered experimental facts, does not to my mind seem to be a very strong indictment of the theory or of its practical value, and possibly was not meant to be such.

The human mind must reason by analogies. To find, not perhaps an *explanation*, but a lucid *description*, of electrical facts, we always resort to some sort of analogy. Thus for years it has been customary to liken an electric current to a water flow in a closed circuit, and to compare certain electric properties to the pressure, volume, and inertia, of water. We have thought in terms of this analogy so constantly that no one arises to say that very likely the term " current " as applied to electricity is meaningless, that it is very improbable that a " quantity " of any tangible substance flows in a wire, or piles up on condenser plates, or acts in the other ways in which we constantly assume that electricity acts. These assumptions are in fact merely a matter of language. It would be impossible to describe electric phenomena, or to teach electrical engineering, without devising a language in which we may talk, and this language must be similar to that in which we speak of more tangible things, even though it be utterly misleading (of course we do not know if it is) if taken in its literal sense as applied to electricity.

Now we find that newly discovered facts, radio-activity, corona effects, etc., etc., demand that we enrich the conventional language with which we describe phenomena. We must therefore have conventional terms, electrons, ions, atoms, molecules, etc., and in order to use these terms so that they may convey some meaning, and always the same meaning, we have a theory. Necessarily the theory will imply mechanical analogies to things that we can see and examine. The theory must, however, be adequate to explain all known facts, and to predict with a considerable degree of accuracy various kinds of phenomena in advance of their occurrence. These requirements are what make the construction of a great new theory like the electron theory so enormously difficult, and make it so valuable or " epoch making " after it has been laboriously put together, tested, modified to fit new data, worked over by dozens or perhaps by hundreds, of brilliant scientists, and finally so perfected that it describes in a consistent language all known physical phenomena, and is reduced to mathematics so that we may " weigh " and " measure " and compute the " velocity " of the various figments of the imagination that we use; and may take a concrete example like a projected transmission line and, by the use of the theory and its mathematics, predict performance with substantial accuracy. It does not matter in the least that the theory may not be really true. The theory is nevertheless indispensible until a better one be produced.

The only danger in a full acceptance of any reasonable theory is, as I believe was first pointed out by Tyndall, that a theory may receive such a weight of authoritative support that a later experimenter may refuse to credit his own results if they seem to overthrow the previously accepted theory, and thus the weight of authority may retard progress, and has in some instances, done so. Sir Isaac Newton developed the corpuscular theory of light, and no one can doubt that that theory was at the time a very valuable aid to the study of light. It was indispensible at the time. Yet there came a time when the weight of Newton's name held back the acceptance of the wave theory after experiments had shown the inadequacy of the corpuscular theory.

We should recognize the fact that no human theory is likely to be completely accurate. I am inclined to suspect that if some superhuman intelligence were to give us the complete solution of the problem of matter, electricity, gravity, light, etc., our minds might not have the capacity to understand. However that may be, our imperfect theories have always been valuable—in fact necessary—to study and progress. When a wealth of new experimental facts discloses a need for some new theory, and the physicists produce a theory that furnishes a possible explanation for all observed phenomena, and a reliable means of predicting new phenomena, we should either produce a better theory, or gratefully accept and use that of the physicists.

The members of the Institute owe a great debt to Professor Ryan for making the electron theory useful to the engineer. It is safe to predict that the physicist also will find this paper of Professor Ryan's constantly valuable for reference. It is seldom that we have a paper of such value.

A. B. Hendricks, Jr.: In the summers of 1903-04 there was carried out at Pittsfield, Mass., under my direction, a series of measurements of corona losses on an experimental high-tension transmission line. These were probably the most elaborate and accurate determinations that had been made up to that time. We used a single-phase experimental line 800 ft. long supported by five pairs of poles and umbrella type insulators of the largest size (about 14 in. diameter).

The following determinations were made:

Variation of loss with

1. Voltage, to 160 kilovolts effective.

2. Diameter of conductor, using copper wires 0.064 and 0.182 in. diameter, galvanized iron cable ⅝ in. diameter and aluminum cable 0.8 in. diameter.

3. Distance between wires 2, 3, 4, 5, 6, 8 and 10 ft.

4. Frequency, measured at 43 and 59 cycles.

5. Atmospheric conditions, showing general effect of fair weather and rain.

The line current was also carefully measured and the critical point for current and loss found to occur at the same voltage and to mark the beginning of loud hissing of the discharge, and in some cases of violent vibration of the conductors. The corona was not observed since the tests were made by day-light.

A typical curve sheet is shown in Fig. 1. The breaks in curves are due to a change in number of high tension transformers used in series, with resulting change in generator load, excitation and wave form. As shown, a power factor up to 0.45 was reached.

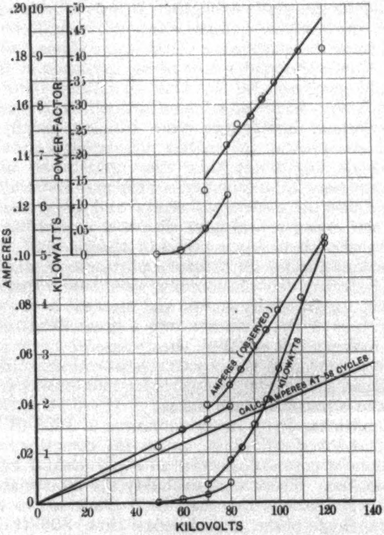

FIG. 1.—Typical curve sheet—variation of loss, current and power factor with voltage for 0.182-in. wires 4 ft. apart—800-ft. line at 58 cycles

Fig. 2 shows variation of loss for conductors 0.064 in. to 0.8 in. diameter, 2 ft. apart, from 70,000 to 130,000 volts.

Fig. 3 shows variation of loss for 0.182-in. wires 2, 3, 4, 5, 6, 8 and 10 ft. apart.

Fig. 4 shows variation of loss for 0.064-in. wires 2 ft. apart at 43 and 59 cycles.

Fig. 5 shows variation of loss for 0.064-in. 0.063 in. wires 6 ft. apart in fair weather and in rain.

In all of these measurements the current was determined by a hot wire ammeter inserted directly into the high-tension line, while the loss was indicated on a wattmeter in generating circuit, thus requiring subtraction of transformer losses from the instrument reading.

Four 40,000-volt transformers and two intermediate insulating transformers were used and great accuracy in results was impossible of attainment especially at the lower losses.

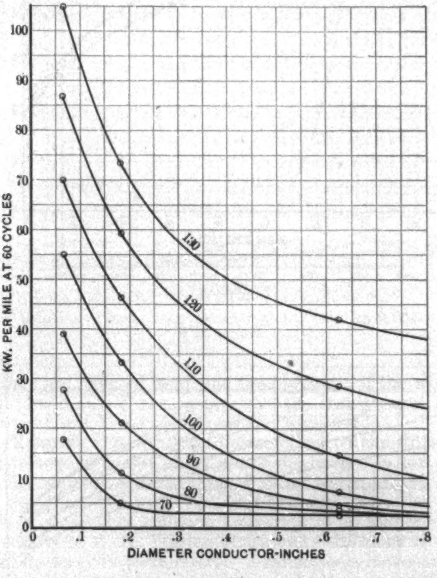

FIG. 2.—Variation of loss with diameter of conductor for wires 0.064 in. to 0.800 in. diameter—2 ft. apart—from 70,000 to 130,000 volts

This difficulty in making accurate measurements led to the design and construction of a new type of high tension transformer especially adapted to this work. In accordance with the suggestion of Dr. C. P. Steinmetz the ammeter and wattmeter are connected at the grounded neutral point of the high tension winding and measure the losses directly with high accuracy.

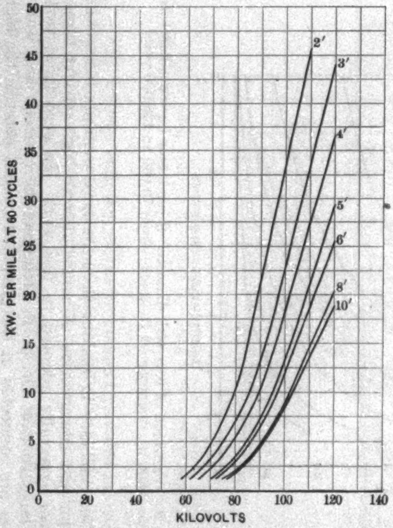

FIG. 3.—Variation of loss with distance between wires for 0.182-in. wires 2, 3, 4, 5, 6, 8 and 10 ft. apart

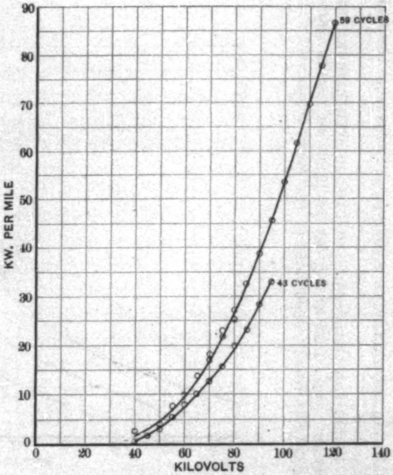

FIG. 4.—Variation of loss with frequency for 0.064-in. wires—2 ft. apart— at 43 and 59 cycles

This transformer and method is now being used by Dr. Steinmetz in a most elaborate series of new determinations, the results of which will undoubtedly be presented to this society.

As the results of my own determinations have never been published, they are referred to at this time because of the wide range of conditions covered, the accuracy of the results, and the very early date at which the measurements were made.

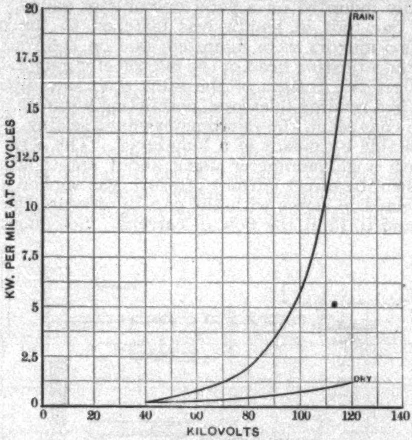

FIG. 5.—Variation of loss in fair weather and in rain for 0.064-in. wires—6 ft. apart

J. A. Koontz: Dr. Sheldon has referred to the difference of opinion in regard to the short spark discharges in air or other gases. By short spark discharge I mean the sparking distance that is less than 11.8×10^{-5} in. (3×10^{-4} cm.) *i.e.*, the distance which is so small that collision ionization is no longer effective.

The results of E. H. Williams[1] are quite different from those obtained by other experimenters. I cannot see, however, wherein his apparatus has superior rigidity nor that he employed as great care and precision as Professor Kinsley did[2]. I believe the work of Williams is open to at least two sources of error.

First, the voltage used to determine zeros was too high.

Second, the contacts were so highly polished that they were covered with a surface film and doubtless the distances from metal to metal, were somewhat greater than the interferometer indicated. These films may have behaved as solid dielectrics.

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[1] *Physical Review*, XXXI, 3, p. 216, 1910.

[2] *Phil. Mag.*, (6) (9) p, 692, 1905.

To follow out these short spark discharge phenomena more clearly for my own satisfaction I used the following simple apparatus: Two hemispherical, chemically pure silver electrodes were rigidly mounted on a good micrometer gauge. A pointer of about one foot in length was fastened to the micrometer head. Two mirrors were mounted, one on the frame and the other on the adjusting head of the micrometer gauge so that they would reflect two images of the same scale one directly above the other in a reading telescope, permitting accurate observation of minute changes in the micrometer gauge setting. The pointer was adjustable by means of a long lever. The zero was determined with a galvanometer using about one-thousandth of a volt. When the direct current pressure was applied a voltmeter was connected in series with the gap to measure the rupturing voltages and to limit the flow of current. See diagram of connections Fig. 1. The electrodes were first polished then cleaned with cyanide and finally thoroughly washed with distilled water, so as to eliminate surface films.

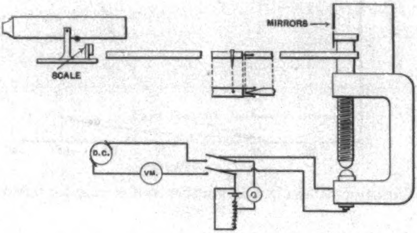

FIG. 1

The zero could be determined to approximately one millionth of an inch by the making or breaking of contact as shown by the galvanometer. It is difficult to determine the exact length of a gap when working with these minute distances because of the peculiar way in which the metallic particles act when subjected to the electric forces, due to the formation of metallic bridges or coherence wires.

When clean metallic surfaces are pressed together the movement of the gauge from a good low resistance contact to a break of contact, *i.e.*, from 0.1 ohm to ∞, is about 11.8×10^{-7} in. (30×10^{-7} cm.). Now if we separate the electrodes about 40×10^{-7} in. (100×10^{-7} cm.) and force a few milliamperes of current across the gap, the surfaces will cohere, *i.e.*, a low resistance metallic bridge will connect them. If the surfaces are then slowly separated the resistance of the bridge will gradually increase and with care they can be separated to a relatively great distance before the coherence will again rupture. The accompanying coherence-resistance curve is taken from Kinsley's report[3] and is quite characteristic of my own results. See Fig. 2. Kinsley, working on the assumption that the coherence wires were of pure platinum, iridio platinum contacts being used, figured the diameter to be 4.4×10^{-6} cm. when $R=2$ ohms. He said therefore that we need not be surprised at our failure to observe with the microscope any evidence of coherence.

Dr. Sheldon refers to Williams' conclusion[4] that moisture lowers the discharge potential for short distances. Williams obtained for his minimum spark voltage 372 volts for dry air while physicists in general obtain correspondingly 350 volts. Williams introduces moisture and succeeds in getting the value of 350 volts and therefore concludes that the other physicists did not dry the air properly. Nevertheless, Kinsley even went so far as to compare the effects of various drying agents. When considering the many difficulties and wide variations obtained in such observations I do not think we are justified in drawing conclusions as to the effect of moisture from the results of Williams.

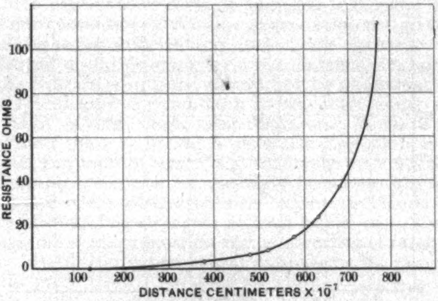

FIG. 2

The average results of quite a number of my own observations of short gap rupturing voltages are plotted in Fig. 3. The results were obtained by the apparatus previously mentioned, no attempt being made to dry the air. The mean of the plotted results gives a value of 2,700 kilovolts per in. Earhart[5], Kinsley[6] and Hobbs[7] obtained a value of 2,500 kilovolts per in. Kinsley obtained values below and above 2,500 kilovolts per in., depending upon the treatment the electrodes received, the drying agent used, etc.

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[3] *Phil. Mag.*, (6) 9, p. 692, 1905.
[4] *Physical Review*, XXXI, 3, p. 216, 1910.
[5] *Phil. Mag.*, (6) 16, p. 48, 1908.
[6] *Phil. Mag.*, (6) 9, p. 692, 1905.

Kinsley came to the conclusion that there is a change in the form of the carriers of the electricity when dealing with distances less than 3×10^{-4} cm. J. J. Thompson[8] holds the view that in these short spark discharges the electrons are dragged out of the metal electrode by the electric field and that ionization by collision is absent.

My own experiments leave no doubt in my mind as to the essential integrity of the Earhart-Kinsley-Hobbs results.

Such thin films of air will rupture under an electric stress of about 2,500 kilovolts per in. (1000 kilovolts per cm.).

The ruptures develop coherence having in itself many interesting properties.

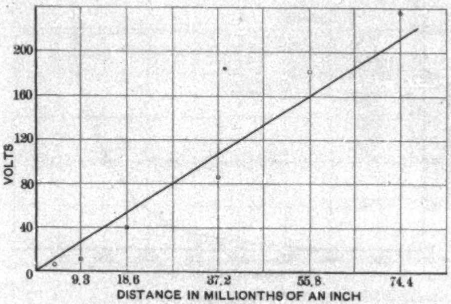

Fig. 3

The results of the various sorts obtained are of such a character and so concordant as to preclude the assumption that they are due to contacts resulting from the electric forces and the elasticity of the apparatus.

C. E. Bennett: In explanation of corona formation in oil and of the difference in corona loss from hard and soft drawn wires, Professor Ryan uses the theory of emission of electrons from the metal as suggested by Thomson to explain the experiments of Erhart and others, on short spark gaps. It seems highly probable that these results were invalidated by lack of rigidity of their apparatus, since it is difficult to secure a mounting which, under electrostatic stresses will not bend as much as

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[7] *Phil. Mag.*, (6) 10, p. 617, 1905.

[8] Conduction of Electricity through Gases, Second Edition, chapter XV.

0.00003 to 0.0003 cm. which is of the magnitude of the electrode distances used.

In 1908, Almy[9] repeated the experiments showing the actual bringing together of the electrodes under the electrostatic attraction at voltages below the minimum potential. Using more rigid apparatus and minute electrodes to decrease the attraction, he failed to find any evidence of spark discharge below the minimum potential. Williams[10] arrives at similar conclusions with a ball and plate and states that "The discharge potential for a distance between electrodes of one wave length of sodium light is the same as for five wave lengths, being in both cases the minimum potential which is 372 volts." And again, "When the distance between the electrodes is very short, 5λ or less (0.00029 cm.) the path of the discharge is not along the shortest distance. Also ionization of the gas between the electrodes lowers the discharge potential." In a research soon to be published in the *Physical Review*, Williams shows that if the air is slightly humid the minimum potential is decreased from 372 to 292 volts.

All these experiments seem to indicate that metal electrodes even under conditions of extreme nearness, do not give out electrons in quantities sufficient to cause spark discharge, otherwise the potential would decrease with the distance, discharge would be at the nearest point, and would not be dependent upon the degree of ionization or moisture in the intervening gas. Experiments in oil point in the same direction. We have long been familiar with the way in which dielectric strength is lowered by very small amounts of water and moderate amounts of carbon. In our laboratory experiments, we have been especially impressed by the same effect with extremely minute bubbles of air, the lowering of dielectric strength, at least in the case of water and air, being out of all proportion to the quantity of foreign matter present. Published experimental data seems too meagre as yet to permit more than a guess as to whether this is a matter of electrolytic or gaseous ionization, mechanical alignment, or something else, but whatever the explanation, it seems reasonably certain that the mechanism of spark discharge must be looked for in the dielectric itself, and it therefore seems hardly necessary or desirable to turn to the metal in explanation of corona.

Harris J. Ryan: The values of a in Fig. 2 constitute the revised values of d that occur in my 1904 paper. By comparing the 1904 values of d with the corresponding values of a Fig. 2 of the present paper, it will be found that they differ appreciably for small conductors, *i.e.*, those having diameters, of 0.1 in. (0.25 mm.) and less. The differences compensate for a change from a variable to a constant corona starting stress of 76 kilovolts per in.

The preparation of the present paper was begun about two years ago. The first work done was in connection with these critical thicknesses of the initial corona zone. The study was undertaken because Mershon in his 1908 paper made a close study of the critical corona forming distances and strains *d* and *D* that I had reported in my 1904 paper.[11] He located the curves in Fig. 48 of this paper with the values of *d*, *D*, and the conductor diameters as tabulated by me. In commenting hereon, he said: " These curves are hardly such as one would accept in connection with physical phenomena. The relations they show would appear to be entirely empirical and of a character to raise some doubt as to the necessity for the assumptions from which they result." In this, I was compelled to agree heartily, and the present study was begun to learn more about the character of the physical phenomena involved in initial corona formation.

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[9] *Phil. Mag.*, September, 1908.

[10] *Phys. Rev.*, September, 1910.

In regard to the experiments with the small concentric cylinders Fig. 3 and the significance of one and of two pairs of cylinders in series: The purpose of these experiments was to compare the values of divergent electric stresses that cause coronas with those that cause sparks of corresponding lengths. In the coronas formed about a high-tension line, there are two divergent corona-forming fields in series; the divergent ends of these fields are adjacent, their convergent ends envelope the conductors. In many actual proportions of electrodes, these divergent and convergent ends of the fields bring about polarity effects in the migration of the electricity carriers: In an alternating circuit this might be thought to produce discrepancies between results obtained in one divergent field and those obtained in two divergent fields, back to back, in series. One needs only to recall the classical experiments, such as the stoppage of sparks between the discharge balls of an electrostatic machine (oscillations suppressed as much as possible) by introducing midway between the balls an insulated conducting plate placed at right angles to their common axis, to realize that doubts might otherwise arise as the value of the alternating spark potentials made on but one cylindrical field in air.

In regard to the vapor-product: Undoubtedly in the open atmosphere it is at all times an indirect gauge of the ionization present and, therefore, a gauge of the cause of variation of the *critical loss voltage* as distinguished from the *critical corona voltage*. The former fluctuates greatly with the supply of ions and the latter on the same account is affected but little. The fundamental cause, however, is not the presence of the aqueous vapor; it is, rather, the ions with which the vapor is associated. The relation between the critical loss voltage and the stock of ions present is direct, and aqueous vapor in the atmosphere is related to such critical loss voltage only as it is related to the stock of ions with which it is known always to be intimately associated. In consequence my claim is, with our present limited knowledge of the relation of the amount of vapor to the amount of ionization in the open atmosphere, that the ionization itself is a more direct and a more dependable gauge of the cause of the variation of the critical loss voltage that Mershon found to be related to the vapor-product than is such vapor-product of itself.

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[11] " High Voltage Measurements at Niagara ", by Ralph D. Mershon, TRANSACTIONS A.I.E.E., Vol. XXVII, II, p. 900, Fig. 48.

I agree fully with Mr. Faccioli that the figure of the field has most to do with discrepancies found in comparing results by experiments with results by formulas. We will no more be able to get along without experimentally determined " coefficients " in this work than the hydraulic engineer can get along without them in his work. As shown in the paper the changes in the figure of the electric field are the greatest cause for the non-agreement heretofore of the results by formulas developed in the laboratory and results by test in the open on the high-tension line. Mr. Faccioli has shown us that the ground connections did not exercise an influence in this respect in his experiments. From this it must not be inferred that the absolute potential will never enter as a factor in these matters. The absolute potential and consequent distortion of electric fields that are being dealt with must always be kept in mind.

In regard to the corona tests on the Central Colorado Co.'s lines, the remarks in my paper relating hereto are based on the data contained in the West communication. Mr. Faccioli's discussion of the same is based on his own corresponding measurements. I note that our views differ just as the data we employed are observed to differ. I firmly believe in the integrity of both sets of data. West's were obtained in the middle and later summer season, at a time when the air over the " divide " is highly electrified, and Faccioli's were obtained in the season when the Sierras, the Rockies and the intermountain region are blanketed by snow and moisture, and the electrification of the atmosphere is much diminished. In the summer in these high altitudes when the pores of the earth are open, the air always blowing eastward over the Sierras and intermountain region becomes most highly charged by the time it passes over the great divide, a matter well known in meteoralogy. This seasonal difference in the electrification of the atmosphere may well be the cause of the differences in the results obtained in the corona tests made by West and Faccioli on these lines.

I quite agree with Dr. Steinmetz that the electron theory is not far enough along in its development so that it can be employed generally to predict results. In fact it is only by the extension of knowledge by experiment that this theory is advancing. However, it must not, therefore, be expected to establish that which it needs for its own establishment. The electron theory is employed in this paper for the purpose of correlating facts giving us a basis for arranging our total knowledge so that its uses may be made more frequent and complete and so that we can more readily and safely decide between results that are dependable and those that are discrepant. I grant most cordially that the master mind making this criticism of the electron theory has little or no need of it as yet. A profound mentality coördinates and employs all knowledge upon which it lays hold in its own way and has less need for or desire to use such a vehicle of mental association as the electron theory in its earlier stages of development. It must always be that opposition to any theory of the sort just noted is among our most valuable assets. To have diverse phenomena ordered and correlated as Dr. Steinmetz has just now done for us speaks for itself the high value of able opposition to a well-started theory.

I formulated my corona conclusions in seven brief statements to be found on the closing pages of the paper. I much prefer those to the conclusions formulated for me by Dr. Whitehead at the beginning of his discussion. The electric intensities producing sparks across cylindrical air gaps having the same proportions as initial corona zones were studied to compare their magnitudes with the electric intensities that produce such coronas. These electric intensities were found to be the same, therefore I said that corona is a glow-spark from the conductor to the air. I had no thought of calling this a corona cause. I did this to bring out the fact that coronas, glow discharges and sparks are intimately related, being fundamentally the same phenomena made to differ in form as the mechanical and electrodynamic effects of the electric carriers are made to differ through change in the physical proportions of electrodes and air gaps.

The evidences that corona covering the negative conductor is started by collision ionization produced by the outward travel of electrons from the cathode conductor surface liberated therefrom by the impact of incoming positive ions, called by the physicists canal rays, are the following:

1. In a vacuum discharge tube with its air pressure at the convenient value of 1/760 in. of mercury, the cathode ceases to discharge electrons from that portion of its surface when positively charged atoms or ions (canal rays) are not allowed to strike it.

2. In the normal atmosphere as shown by Nipher in the classical experiment of preventing the passage of strong sparks between the discharge balls of an electrostatic machine by the interposition of an insulated metal plate which prevents a larger portion of the canal rays from striking the negative discharge ball.

3. By the studies of the cathode corona a' and a'' emanating from the cathode spots b' and b'' in connection with Figs. 20, 21, 22, 23, 24*a* and *b*, and 25, in the normal atmosphere reduced to a pressure of 3 in. on the mercury column. These were spark discharges. Precisely the same though less convenient studies can be made with coronas, where one of the positive electrodes is always the enveloping air into which the collision ionization has not extended.

4. The sensitiveness of the cathode corona to any radioactive

substance at the surface of the cathode conductor known to be liberating electrons is evidence that out-going electrons at such surface promote the development of cathode corona. These effects are not found at the anode conductor because the corona there is inaugurated by incoming electrons producing collision ionization.

5. The visual characteristic difference of the coronas over the negative and positive conductors is evidence of the same character, *viz.*, that the one is started by out-going electrons in collision, and the other by incoming electrons in collision. The initial corona about the cathode conductor is of an irregular tufted, brush character and that about the anode conductor is short uniform, and flat against the conductor. (Remember that each is due to the movement of electrons in collision crossing first a cathode dark space in which the collision ionization action gathers headway resulting in the production of glow or brush. This is the reason why the negative corona is not flat against the cathode conductor and the positive corona is flat against the anode conductor. What liberates these electrons at the surface of the cathode conductor that, travelling outward, produce, by collision ionization, the cathode corona?)

Dr. Whitehead says these are not conclusive evidences that the electrons departing from the surface of the cathode conductor are liberated thereat by the impact of the incoming positive ions (canal rays). Of course, every man has the right to decide for himself when the evidence is sufficient. I hope that he can give us more evidence as to this vital point, and that will be in his estimation conclusive as to the source of the outgoing electrons which produce the corona that covers the cathode conductor. To me this evidence is not all of the kind and amount that I would like to have, nevertheless in the general circumstances of the case it is reasonably conclusive.

As to Dr. Whitehead's dissatisfaction with the experiment in connection with the No. 12 high-tension wires and the No. 30 negatively charged wire between them, Fig. 28. Doubtless there is some modification of the electric field produced by the change in the absolute potential and by the presence of the additional supply of migrating electrons. That is just the point in the experiment, the cause for my satisfaction instead of a lack thereof. That I am not alone herein is shown by the comments of Mr. Noeggerath.

If there is one thing I have emphasized strongly in my paper and in the conclusions at its close, it is that ionization by collision is the cause of corona and that the critical balanced visual corona voltage (not critical loss voltage; that is another thing) is not affected by considerable variation in the amount of antecedent ionization. Dr. Whitehead introduces his interesting and valuable experiment with Roentgen rays with comments that would lead the reader to understand that we differ as to this point. On the contrary his experiment supports in the strongest manner one of my most important conclusions.

Dr. Whitehead's statement that spark discharging intensities at electrode surfaces in the normal atmosphere under some circumstances are higher than 76 kilovolts per in. is misleading as it stands. They are higher in a uniform electric field only when the gaps are shorter than the critical gap-length, and when the electric field is divergent, convergent or both in series. In the former case the electric intensity has had to be raised by lessening the minimum distance required in which to build up the full state of collision ionization. In the latter case, besides the intensity of 76 kilovolts per in., that starts collision ionization for the longer sparks, an additional stress is required to increase the quantity of ions thus formed sufficient to produce a core. The initial transport of such core takes further toll, not through electric intensity at the conductor surface, but through added voltage which supplies the drop along the resulting spark length. Undoubtedly then one does find electric intensities at initial corona zone distances from the conductors surfaces required to produce sparks that are greater than 76 kilovolts per in. for the reason just given, a matter that was not directly brought up in the paper for it was thought to follow as a matter of course. The spark intensities referred to in the paper had to do with spark distances equal to initial corona zone thicknesses. I am glad that Dr. Whitehead has forced this emphasis of the distinction between the two classes of sparks. All this does not alter in the least the fact that a stress of 76 kilovolts per in., approximately in the normal air is sufficient to start collision ionization except at smaller than critical distances. The ionization may not be enough to produce a core and thus to develop into a spark—added intensity may be necessary for that. Great increase in conduction will promptly and certainly result in the normal atmosphere that is pervaded with a minimum stress of 76 kilovolts per in., for a distance greater than the critical distance upon slightest increase in voltage. I have never found evidence to the contrary.

In concluding my reply to Dr. Whitehead, I wish to insist cordially that there is no important difference in our understanding of these matters when we get together on terms and ways of talking about things. Naturally when I say that changes in antecedent ionization will produce corresponding changes in the *critical loss voltage*, and he understands thereby that I am referring to the *uniform balanced critical corona voltage*, that he observes in the laboratory to be unaffected by Roentgen rays he concludes that I am quite wrong and informs us so in emphatic terms, yet each has referred to a totally different thing —the only cause of the discrepancy. This of course is a difficulty quite natural in such a new subject. It will pass quickly enough. Dr. Whitehead's is the first corona paper to employ our knowledge of the behavior of electrons and the ions they produce. It is of high value on that account and because of its thorough-going integrity within its own limits.

I fully expected that the family difference among our friends the physicists, in regard to the results of Erhart, Kinsley, Hobbs and Shaw, supported by J. J. Thomson, would come up, and I hesitated at first to use Erhart's results on this account, because of the confusion that it inevitably must leave in the mind of the average reader of the TRANSACTIONS. When I found that a prominent intelligence transmission engineer in England had made practical use of the Erhart result in such proportions as to eliminate the erratic character of coherence that follows the Erhart discharge, so as to produce a marvellously successful telephone repeater, I felt that Erhart's values should be used to support my own for the intensities (2500 kilovolts per in.; 1000 kilovolts per cm.) that liberate the free electrons from a metal electrode into surrounding gas.[12] I have now gone over these papers (see Dr. Sheldon's references) and we have worked with the minute gaps, using silver electrodes, so that we might better understand the papers, especially that of Williams. It is a long story, a whole paper in itself, as to the rational cause for the family quarrel of the physicists over the point. The chief cause of the difficulty is the make-up of the actual surface of a polished metal. Such a surface has a complicated character. Erhart, Kinsley and others, with superb experimental strategy, used electrical coherence to draw some of the metal of the electrodes through the surface films so that the discharges were made to pass truly from metal to metal across distances less than one fifty-thousandth of an inch. Williams, in an otherwise beautiful work, refused such strategy, and so obtained negative results. His discharges are all collision ionization discharges in which there appears an excess voltage required to batter down the surface film produced by polishing or other treatment or condition. Mr. Noeggerath in his remarks gives independent confirmation of the existence of such surface film, likewise of the conduction by free electrons or ions across these extremely short gaps. Time does not permit, and space in the TRANSACTIONS would not permit me to take up these matters fully. I have studied them with some care and will say that in my judgment the physicists have shown that a stress of about 2500 kilovolts per in. is required to cause electrons to pass from the exposed surface of a metal electrode to a gas in which it is immersed.

Taking up Dr. Sheldon's comments on Fig. 17*b*: I introduced that chart for general interest. I found that the records were hardly clear enough to warrant a computation of the electric strain about the needle points at which the rise in kilovolts per in. against pressure per sq. in. in CO_2 ceases for the first time.

In regard to Dr. Kennelly's contribution to corona discussion:

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[12] The Brown Telephone Relay. S. G. Brown, The Institution of Electrical Engineers. Presented in May, 1910. Jour, 45, pp. 590–601, Sept. 1910. Also Sci. Abs. Dec. 1910 No. 1101 p. 470.

At the White Mountains Convention last July, Dr. Kennelly in discussing Dr. Whitehead's papers brought forward as a corona factor the liklihood that an ion will travel faster in a convergent than in a divergent electric field. In preparing my paper I had not noticed this perception of Dr. Kennelly's of the cause of the accumulation and retention of a stock of ions in the atmosphere in the open about the conductors of a high-tension transmission. He has clearly and strongly anticipated my own conclusion in the matter.

Mr. Peek has kindly given me the structural data pertaining to the experimental line referred to in connection with his Figs. 1. and 2. Using these for substitution in equation No. 3 of the present paper wherein the irregularity factor is taken at 0.75, the critical corona voltage is computed to be 155 kilovolts while Mr. Peek reports that the visual critical corona voltage was observed to be 157 kilovolts as an experimental check. That he found the *temperature reciprocal to critical voltage relation* at stationary barometer on the large out-door high-tension experimental line, to be rectilinear, passing through zero on the absolute scale of temperatures, is most important in the corona problem of the engineer. This corroborates on a large practical scale my laboratory conclusions of 1904, and will cause practicing engineers to have confidence in the definite corona temperature factor.

Referring to Mr. Hendrick's contribution; through a former coworker of his I have profited since the presentation of my paper, by an opportunity to look over the original series of data curve sheets from among which his Figs. 1-5 were taken. They constitute a valuable addition to our corona data collection. After allowing for the high-voltage wave form factors, they check up at all points that I have tried for integrity.

A paper presented at the 255th meeting of the American Institute of Electrical Engineers, New York, February 10, 1911.

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ADVANTAGES OF UNIFIED ELECTRIC SYSTEMS COVERING LARGE TERRITORIES

BY WILLIAM B. JACKSON

A few years ago the advantages of electric light and power were considered to belong to cities and the larger towns alone, but it is becoming recognized that with properly organized companies and with plants suitably planned the benefits of electric lighting and power may be supplied at reasonable cost also in sparsely settled regions.

To provide electric light and power for a densely settled district, except in cases of very large cities, is comparatively simple, for this requires an organization and plant for a limited and homogeneous community. But for the larger possibilities of service, which means the tying together of many cities and towns, villages, and even outlying homesteads, by a great network of transmission and distribution lines, a more complex problem is presented.

To realize one of the material operating advantages of unified electric systems, the general direction of the operations of the company must be centralized, while the local characteristics and requirements of each community must be intimately considered, if the most satisfactory service is to be provided. This requires an organization controlled by exceptionally broad and discriminating engineering and commercial judgment.

Several factors tend toward making it economically possible to serve any territory from a comprehensive transmission and distribution system as a substitute for disconnected central stations located in the cities and villages. These may be here summarized as follows:

1. Saving in power house equipment made possible through

taking advantage of the diversity of different communities by serving them from the same transmission system.

2. Lower power generating cost per kilowatt-hour due to larger power plants and improved load factor.

3. Less investment in power plants per kilowatt capacity on account of larger plants as compared with smaller.

4. The possibility of decreased percentage of spare apparatus by appropriate arrangement of power plants.

5. Saving in cost made possible by centralized management, general superintendence and other general expenses.

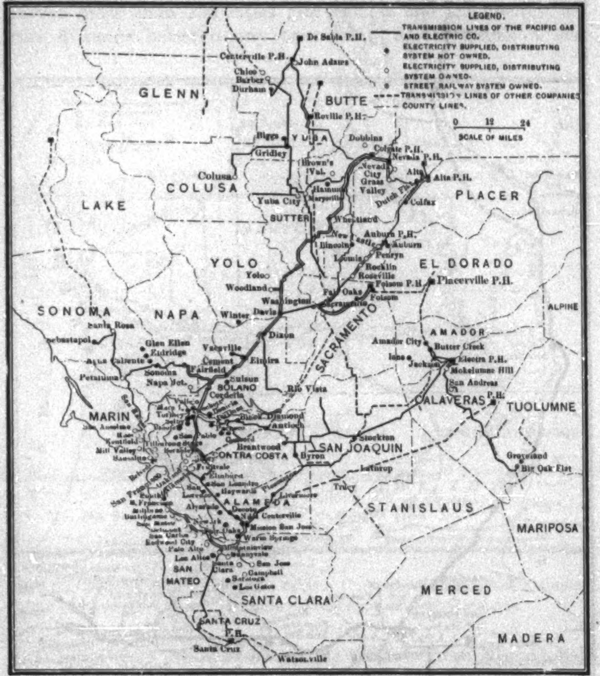
6. The possibility of providing rural and suburban service that could not be profitably reached by a local central station.

7. The possibility of large corporations providing power service which would be too extensive for small companies to undertake.

8. The development of water powers for electric service.

The savings made available by the above may be set against the losses occasioned by the transmission transformers and lines and the cost for their current maintenance, deferred maintenance and interest on investment, to determine whether a unified system or a number of separate plants can most economically serve a territory. But it should be borne in mind that only by covering the country by electric circuits for comprehensively serving groups of cities and villages from relatively large power houses, stragetically located, is it possible to serve rural districts generally with electric light and power at reasonable cost. It is seldom economically possible to serve a rural district alone, just as it is impossible to provide electric railroad service to such a district without considering terminal cities.

The practicability of serving by electric transmission systems large territories comprising all kinds of communities, urban, suburban, and rural, was first demonstrated by hydroelectric developments from which the transmission of the power was necessary in order to obtain a market. Astonishing development has occurred in such systems since their introduction only a few years ago. It is eighteen years since the first commercial electric transmission plant in the United States using 10,000 volts or over was started at Pomona, Cal., while it was three years later when the first such plant east of the Rocky Mountains began transmitting electric power from Lowell to Grand Rapids, Mich. The transmission from Niagara Falls to Buffalo was put into operation shortly thereafter. To-day the state or territory within which important hydroelectric transmission systems are not found is an exception. In less than fifteen years the generation of electric power from water powers and its transmission and distribution has become an important industry in almost all sections of the United States. And it has carried the benefits of electricity to many regions that otherwise could not be served.


LEGEND.
TRANSMISSION LINES OF THE PACIFIC GAS AND ELECTRIC CO.
● ELECTRICITY SUPPLIED, DISTRIBUTING SYSTEM NOT OWNED.
○ ELECTRICITY SUPPLIED, DISTRIBUTING SYSTEM OWNED.
● STREET RAILWAY SYSTEM OWNED.
TRANSMISSION LINES OF OTHER COMPANIES
COUNTY LINES.
0 12 24
SCALE OF MILES
De Sabla P.H.
Centerville P.H.
John Adams
Chico
Barber
Durham
GLENN
BUTTE
Oroville P.H.
Biggs
YUBA
Dobbins
Gridley
Colgate P.H.
Nevada P.H.
Brown's Val.
Nevada City
Grass Valley
Alta
Alta P.H.
Colusa
COLUSA
Hammonton
Marysville
Dutch Flat
Colfax
PLACER
LAKE
Yuba City
SUTTER
Wheatland
Newcastle
Lincoln
Auburn P.H.
Auburn
Penryn
Loomis
Rocklin
Roseville
YOLO
Yolo
EL DORADO
Placerville P.H.
Woodland
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SONOMA
NAPA
Winters
Davis
SACRAMENTO
Santa Rosa
Sebastopol
Dixon
Glen Ellen
Eldridge
Vacaville
Amador City
AMADOR
Butter Creek
Agua Caliente
Cement
Elmira
Ione
Jackson
Electra P.H.
Mokelumne Hill
Petaluma
Sonoma
Napa Jct.
Fairfield
Suisun
SOLANO
Cordelia
Rio Vista
San Andreas
CALAVERAS
P.H.
TUOLUMNE
MARIN
Vallejo
Black Diamond
Antioch
San Anselmo
Mill Valley
Sausalito
San Pablo
Concord
Stockton
SAN JOAQUIN
Brentwood
CONTRA COSTA
Byron
Groveland
Big Oak Flat
Lathrop
Fruitvale
Elmhurst
San Leandro
Haywards
Pleasanton
Livermore
Tracy
San Francisco
Oakland
Alameda
ALAMEDA
STANISLAUS
Alvarado
Decoto
Niles
Centerville
Mission San Jose
MARIPOSA
Newark
Warm Springs
San Carlos
Redwood City
Palo Alto
Mountain View
Sunnyvale
Los Altos
Santa Clara
San Jose
Campbell
Saratoga
Los Gatos
SAN MATEO
MERCED
SANTA CLARA
SANTA CRUZ
P.H.
MADERA
Santa Cruz
Watsonville

FIG. 1.—Transmission lines of the Pacific Gas & Electric Company, Central California

The wide distribution and scope of service of our hydroelectric systems is illustrated by the following brief consideration of a few representative systems.

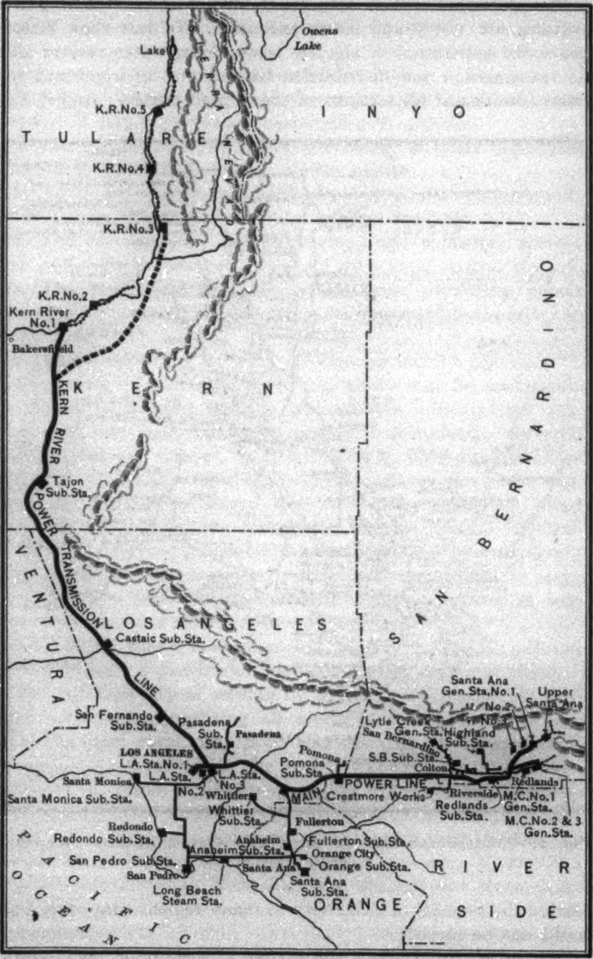
Owens Lake
Lake
SIERRA NEVADA
K.R.No.5
TULARE
INYO
K.R.No.4
K.R.No.3
K.R.No.2
Kern River No.1
Bakersfield
KERN
KERN RIVER POWER TRANSMISSION LINE
Tajon Sub.Sta.
SAN BERNARDINO
VENTURA
LOS ANGELES
Castaic Sub.Sta.
San Fernando Sub.Sta.
Pasadena Sub. Sta.
Pasadena
LOS ANGELES
L.A.Sta.No.1
L.A.Sta. No.2
L.A.Sta. No.3
Santa Monica
Santa Monica Sub.Sta.
Whittier
Whittier Sub.Sta.
MAIN POWER LINE
Pomona
Pomona Sub.Sta.
Crestmore Works
Lytle Creek Gen.Sta.
San Bernardino
S.B.Sub.Sta.
Colton
Highland Sub.Sta.
Santa Ana Gen.Sta.No.1
No.2
No.3
Upper Santa Ana
Redlands
Riverside
Redlands Sub.Sta.
M.C.No.1 Gen.Sta.
M.C.No.2 & 3 Gen.Sta.
Fullerton
Fullerton Sub.Sta.
Anaheim
Anaheim Sub.Sta.
Orange City
Orange Sub.Sta.
Santa Ana
Santa Ana Sub.Sta.
Redondo
Redondo Sub.Sta.
San Pedro Sub.Sta.
San Pedro
Long Beach Steam Sta.
PACIFIC OCEAN
ORANGE
RIVERSIDE

FIG. 2.—Transmission system of the Southern California Edison Company

In the region tributary to San Francisco and Sacramento the transmission and distribution system of a single company serves a district comprising fully 12,000 square miles (31,080 sq. km.), which is an area 50 per cent greater than the entire state of Massachusetts. Broadly speaking, the territory tributary to the circuits is nearly three times as great an area. The company serves more than 150 cities and villages and the greatest air-line distance between any two points on its system is over 200 miles (321 km.), or about the distance from Niagara Falls to Utica, New York. Much of the region served could not economically receive the benefits of electric service except by some comprehensive system such as that under consideration. The extent of this system together with others in this territory are shown in Fig. 1.

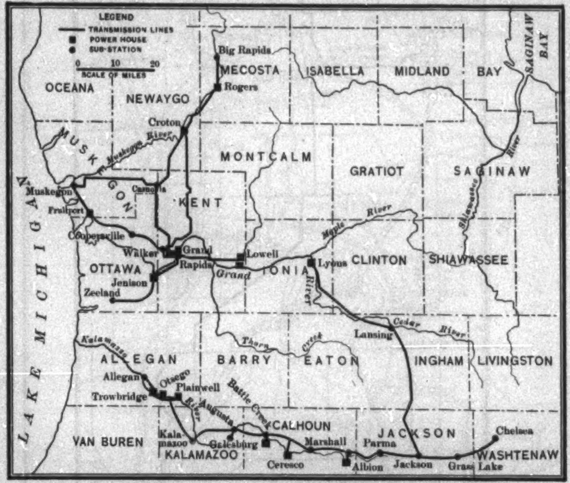
LEGEND
TRANSMISSION LINES
POWER HOUSE
SUB-STATION
0 10 20
SCALE OF MILES
OCEANA
NEWAYGO
MECOSTA
ISABELLA
MIDLAND
BAY
SAGINAW BAY
Big Rapids
Rogers
Croton
Muskegon River
MUSKEGON
MONTCALM
GRATIOT
SAGINAW
Saginaw River
Shiawassee River
Muskegon
Casnovia
KENT
Fruitport
Coopersville
Walker
Grand Rapids
Lowell
Grand River
IONIA
Lyons
Maple River
CLINTON
SHIAWASSEE
OTTAWA
Jenison
Zeeland
LAKE MICHIGAN
Lansing
Cedar River
Thorn Creek
Kalamazoo River
ALLEGAN
BARRY
EATON
INGHAM
LIVINGSTON
Allegan
Otsego
Plainwell
Trowbridge
Battle Creek
Augusta
CALHOUN
JACKSON
Chelsea
VAN BUREN
Kalamazoo
KALAMAZOO
Galesburg
Marshall
Parma
WASHTENAW
Ceresco
Albion
Jackson
Grass Lake

FIG. 3.—Transmission systems of the Commonwealth Power Company and the Grand Rapids—Muskegon Power Company

The Los Angeles and Redlands district is served by two great electrical systems which cover an area of fully 1,000 square miles (2,590 sq. km.) and provide electric service throughout the entire district, city and rural. The larger of these is shown in Fig. 2.

In the middle west, the two electric power companies in the vicinity of Grand Rapids and Battle Creek, Michigan, are good examples of well developed and rapidly expanding hydroelectric systems. These serve 25 cities and villages ranging in size from 90 inhabitants to 112,000 inhabitants, twelve of the villages having populations of less than 1,250 each. These companies

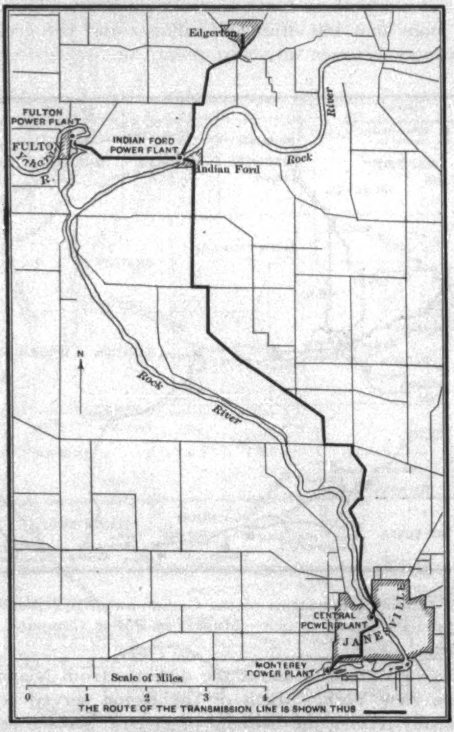
Edgerton
FULTON POWER PLANT
FULTON
Yahara R.
INDIAN FORD POWER PLANT
Indian Ford
Rock River
N
Rock River
CENTRAL POWER PLANT
JANESVILLE
MONTEREY POWER PLANT
Scale of Miles
0
1
2
3
4
THE ROUTE OF THE TRANSMISSION LINE IS SHOWN THUS

FIG. 4.—Transmission system of the Janesville Electric Company, Janesville, Wis.

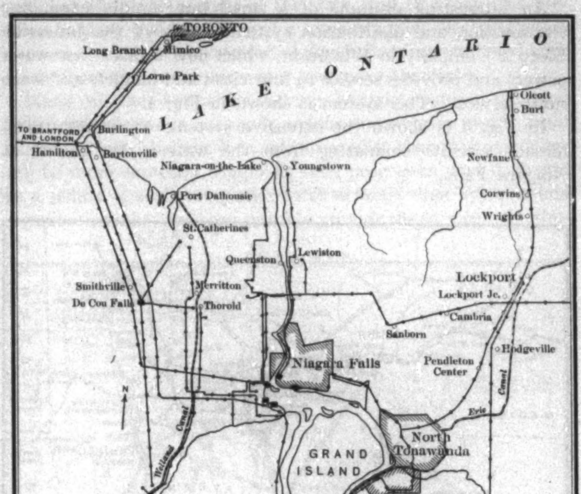
TORONTO
Long Branch
Mimico
Lorne Park
LAKE ONTARIO
TO BRANTFORD AND LONDON
Burlington
Hamilton
Bartonville
Niagara-on-the-Lake
Youngstown
Olcott
Burt
Newfane
Corwins
Wrights
Port Dalhousie
St. Catherines
Queenston
Lewiston
Lockport
Lockport Jc.
Cambria
Smithville
Merritton
De Cou Falls
Thorold
Sanborn
Hodgeville
Pendleton Center
Niagara Falls
N
Canal
Erie
Erie Canal
Welland Canal
GRAND ISLAND
North Tonawanda
Tonawanda
Welland
Bridgeburg
Depew
Fort Erie
BUFFALO
Lancaster
Port Colborne
LAKE ERIE
LEGEND
TRANSMISSION LINE
POWER STATION
Angola
Hamburg
Dunkirk
Farnham
Silver Creek
Erie
Westfield
Fredonia

FIG. 5.—Electric transmission lines in the vicinity of Niagara Falls

also provide power for a number of interurban and city railroads. A map of the systems is shown in Fig. 3.

An interesting example of a small but rapidly expanding transmission and distribution system is that of the Janesville Electric Company in Wisconsin, which now utilizes four water powers and provides service to four cities and hamlets and some rural service. This system is shown in Fig. 4.

In Fig. 5 is shown the extensive systems of electric transmission circuits emanating from the water-power plants at Niagara Falls.

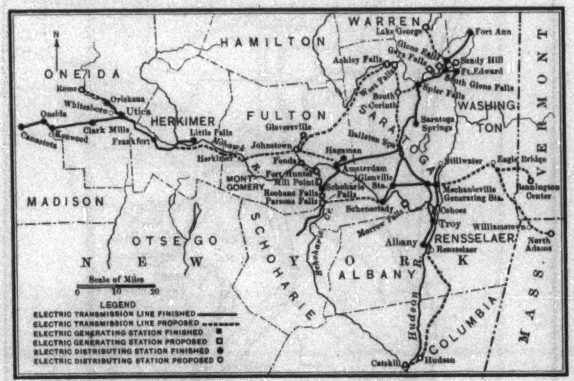
N
ONEIDA
HAMILTON
WARREN
Lake George
Fort Ann
Glens Falls
Gays Falls
Ashley Falls
Sandy Hill
Ft. Edward
South Glens Falls
West Falls
South Corinth
Spier Falls
Rome
Oriskana
Whitesboro
Utica
Oneida
Canastota
Kenwood
Clark Mills
HERKIMER
Frankfort
Little Falls
Mohawk R.
Herkimer
FULTON
Gloversville
Johnstown
Fonda
Fort Hunter
Mill Point
MONTGOMERY
Hagaman
Amsterdam
Glenville Sta.
Schoharie Falls
Rooban Falls
Parsons Falls
SARATOGA
Saratoga Springs
Ballston Spa
WASHINGTON
Stillwater
Eagle Bridge
Bennington Center
Mechanicville Generating Sta.
Schenectady
Morrow Falls
Cohoes
Troy
Williamstown
North Adams
RENSSELAER
Albany
Rensselaer
VERMONT
MADISON
OTSEGO
NEW YORK
SCHOHARIE
Schoharie Cr.
ALBANY
Hudson R.
COLUMBIA
MASS.
Catskill
Hudson
Scale of Miles
0
10
20
LEGEND
ELECTRIC TRANSMISSION LINE FINISHED
ELECTRIC TRANSMISSION LINE PROPOSED
ELECTRIC GENERATING STATION FINISHED ■
ELECTRIC GENERATING STATION PROPOSED □
ELECTRIC DISTRIBUTING STATION FINISHED ●
ELECTRIC DISTRIBUTING STATION PROPOSED ○

FIG. 6.—Electric transmission lines of the Hudson River Electric Power Company

In the East the effect of hydroelectric development in bringing to large territories service from single comprehensive electric systems is well illustrated by the system of the Hudson River Electric Power Company which is shown in Fig. 6. This company serves 13 cities and villages together with a large mileage of electric railroads.

In the South, the Southern Power Company has created a remarkable electric system in North and South Carolina which is shown in Fig. 7.

Fig. 8 shows a map which was the result of a somewhat extended trip of the writer over the rivers of South Carolina in

1902. Estimates were made of the available power of a large number of the shoals and falls together with the power consumed in the various cities of the state, and this map was prepared to show the possibility of a comprehensive electric system to cover the cotton mill section of South Carolina, supplied with power from the numerous water powers of the state.

Many of the companies having electric systems covering large territories have not made serious endeavor to obtain rural patronage but I believe it is safe to predict that this patronage will be more earnestly sought as time progresses, and it should be a policy of such companies to so arrange their systems and organizations that they can suitably provide the service. Hydroelectric transmission companies are benefited by the advantages incident to serving numerous communities from single comprehensive transmission systems, but with them such systems grow up as a matter of necessity along with the development of the water powers, since the creation of transmission systems is necessary to the development of the water powers and the nearest markets are naturally sought for the output of the plants.

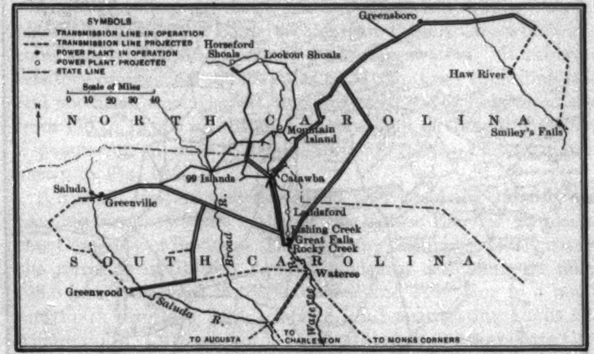
SYMBOLS
TRANSMISSION LINE IN OPERATION
TRANSMISSION LINE PROJECTED
POWER PLANT IN OPERATION
POWER PLANT PROJECTED
STATE LINE
Scale of Miles
0 10 20 30 40
N
Greensboro
Horseford Shoals
Lookout Shoals
Haw River
NORTH CAROLINA
Mountain Island
Smiley's Falls
99 Islands
Catawba
Saluda
Greenville
Landsford
Fishing Creek
Great Falls
Rocky Creek
SOUTH CAROLINA
Broad R.
Wateree
Greenwood
Saluda R.
Wateree
TO AUGUSTA
TO CHARLESTON
TO MONKS CORNERS

FIG. 7.—Electric transmission lines of the Southern Power Company

The requirements of hydroelectric transmission companies gave such impetus to the development of reliable and economical transmission methods and apparatus, that within a score of years the transmission of electric current at high voltages and for long distances has been advanced from the experimental stage to a position of prime importance During this period equal advances have been made in methods of distributing electric light and power to widely scattered customers.

With the perfecting of electric transmission and distribution methods came consideration of the practicability of displacing small central stations by electric current transmitted from relatively large steam generating stations. With hydroelectric plants it is necessary to transmit the water-generated power from points fixed without regard to the markets, and to compete with or displace local steam powers. Much the same conditions exist with steam-electric transmission plants except that the locations of the power plants may be influenced by the locations and characters of the market.

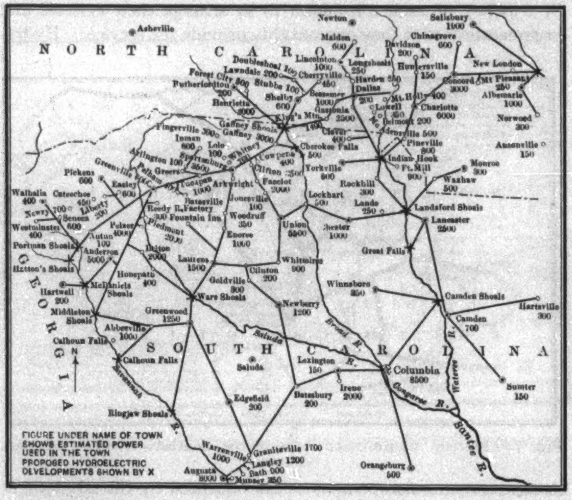
Asheville
NORTH CAROLINA
Newton
Salisbury 1900
Maiden 600
Chinagrove 600
Davidson 200
Lincolnton 1000
Longshoals 250
Huntersville 150
New London
Doubleshoal 100
Lawndale 200
Cherryville 450
Harden 250
Dallas 200
Forest City 800
Stubbs 100
Rutherfordton 200
Bessemer 1000
Concord 3000
Mt Pleasant 250
Albemarle 1000
Shelby 600
Mt. Holly 400
Lowell 350
Charlotte 6000
Henrietta 3000
King's Mtn. 1400
Gastonia 2500
Belmont 200
Norwood 300
Gaffney Shoals
Gaffney 3000
Clover 400
McAdensville 500
Pineville 800
Ansonville 150
Fingerville 300
Inman 600
Lolo 100
Whitney 700
Cherokee Falls 500
Arlington 100
Spartanburg 3500
Cowpens 400
Indian Hook
Ft. Mill 900
Monroe 300
Greenville
Pelham
Greers
Clifton 2500
Yorkville 600
Waxhaw 500
Pickens 600
Easley 600
Tucapau 1000
Arkwright
Fasclot 2000
Rockhill 300
Walhalla 400
Cateechee 450
Liberty 200
Batesville
Jonesville 100
Lockhart 500
Lando 250
Landsford Shoals
Newry 700
Seneca 600
Reedy R. Factory
Fountain Inn 300
Woodruff 350
Union 5500
Chester 1000
Lancaster 2500
Westminster 400
Pelzer 4000
Piedmont 2000
Autun 100
Enoree 1000
Portman Shoals
Anderson 5000
Belton 2000
Great Falls
Laurens 1500
Whitmire 900
GEORGIA
Hatton's Shoals
Honeapath 400
Clinton 200
Goldville 300
Winnsboro 250
McDaniels Shoals
Hartwell 200
Ware Shoals
Camden Shoals
Newberry 1200
Hartsville 300
Middleton Shoals
Greenwood 1250
Camden 700
Abbeville 1000
Saluda
Broad R.
Calhoun Falls
SOUTH CAROLINA
N
Calhoun Falls
Saluda
Lexington 150
R.
Columbia 8500
Wateree R.
Irene 2000
Sumter 150
Edgefield 200
Batesbury 200
Congaree R.
Savannah R.
Ringjaw Shoals
Santee R.
Warrenville 1000
Graniteville 1700
Langley 1200
Augusta 8000
Bath 900
Munsey 250
Orangeburg 500

FIGURE UNDER NAME OF TOWN
SHOWS ESTIMATED POWER
USED IN THE TOWN
PROPOSED HYDROELECTRIC
DEVELOPMENTS SHOWN BY X

FIG. 8.—Proposed universal electric system for South Carolina

Considerable territory is now covered by electric transmission lines receiving power from steam plants and its extent is steadily increasing. Wherever transmission lines are found, electric service should be available for the local customers; and every extension made to a transmission system should mean the opening up of new districts to electric service. In the vicinity of many of our large cities and of some of our smaller ones such systems are now found.

A fine example of a well developed and rapidly expanding system, emanating from steam power plants, is that of the North Shore Electric Company which serves a district covering 1,200 square miles (3,108 sq. km.) surrounding the City of Chicago. It supplies electric current to 60 cities and towns varying in population from 27,000 to 100 people each. Nineteen of these have less than 1,000 inhabitants each, and it is doubtful if one-third of the towns could have adequate electric service were it necessary for them to depend upon local central stations for supply. A map of this system is shown in Fig. 9.

Another system, the major portion of which is fed from steam plants, is that of the Eastern Michigan Edison Co., which is a comparatively new and rapidly expanding system. It covers a territory of over 900 square miles (2,331 sq. km.) extending east and northeast from Detroit, and serves 19 towns ranging in size from 150 to 19,000 inhabitants. Only eight of these towns have a population of over 1,200 inhabitants each. This system is shown in Fig. 10.

A system that is well developed and has been steadily expanding for many years is that of the Edison Electric Illuminating Company of Boston. The company comprehensively covers the territory of Boston and its environs, extending 24 miles (38.6 km.) westward from the harbor and extending in a north and south direction 26 miles (41.8 km.) aggregating about 625 square miles (1,618 sq. km.). In addition to the corporate City of Boston, which has a population of over 670,000 inhabitants, the company serves 35 cities and towns ranging in population from 800 to 77,000 inhabitants. Of these municipalities, nine have populations of less than 2,000 people each, 26 have less than 10,000 inhabitants each, and five (besides the City of Boston) have over 25,000 inhabitants each. Many of these municipalities contain within their borders a number of villages or hamlets which are more or less distinct from each other. Much of the territory is densely populated, but the townships comprising about one-third of it have a population averaging less than 100 people per square mile. The system is shown in Fig. 11.

The above instances serve to illustrate the strides that have been made in the development of extensive transmission sys-

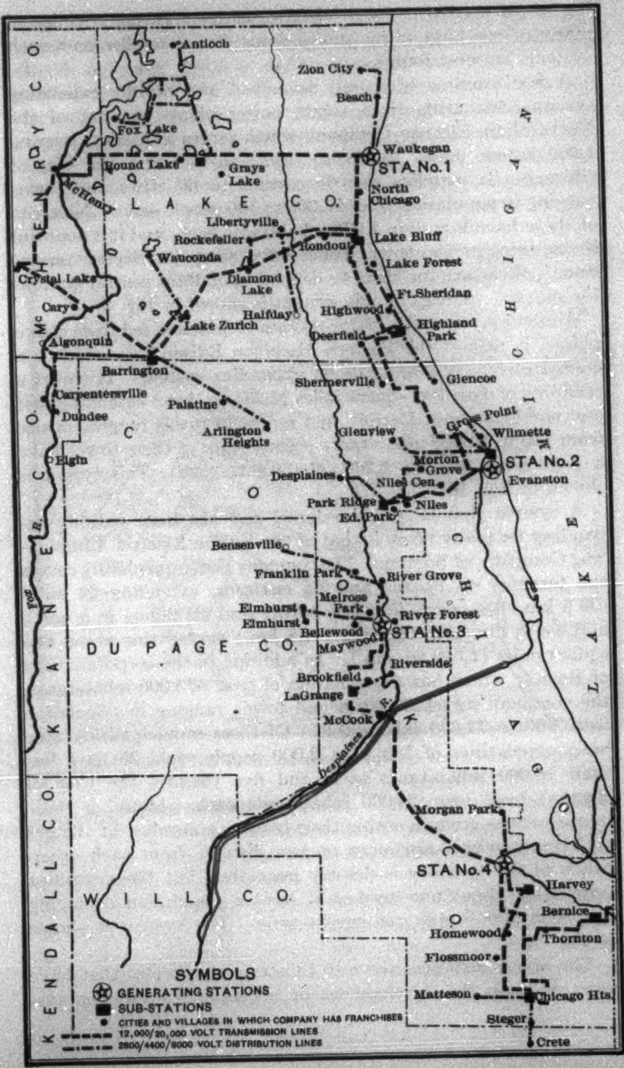
Antioch
Zion City
Beach
Fox Lake
Waukegan
STA. No. 1
Round Lake
Grays Lake
McHenry
LAKE CO.
North Chicago
Libertyville
Rockefeller
Rondout
Lake Bluff
Wauconda
Lake Forest
Diamond Lake
Crystal Lake
Ft. Sheridan
Cary
Halfday
Highwood
Lake Zurich
Highland Park
Algonquin
Deerfield
Barrington
Glencoe
Shermerville
Carpentersville
Palatine
Dundee
Gross Point
Wilmette
Arlington Heights
Glenview
Elgin
Morton Grove
STA. No. 2
Evanston
Desplaines
Niles Cen.
Park Ridge
Niles
Ed. Park
Bensenville
Franklin Park
River Grove
Melrose Park
Elmhurst
Elmhurst
River Forest
Bellewood
STA. No. 3
DU PAGE CO.
Maywood
Riverside
Brookfield
LaGrange
McCook
Desplaines R.
Morgan Park
STA. No. 4
Harvey
WILL CO.
Bernice
Homewood
Thornton
Flossmoor
Matteson
Chicago Hts.
Steger
Crete
McHENRY CO.
KANE CO.
Fox R.
KENDALL CO.
COOK CO.
LAKE MICHIGAN
SYMBOLS
GENERATING STATIONS
SUB-STATIONS
CITIES AND VILLAGES IN WHICH COMPANY HAS FRANCHISES
12,000/20,000 VOLT TRANSMISSION LINES
2300/4400/6600 VOLT DISTRIBUTION LINES

FIG. 9.—Transmission lines of the North Shore Electric Company, Chicago, Ill.

tems fed from steam plants. Considering the material progress that has been made by electric transmission and distribution companies, one may truthfully say that a start has been made toward covering the rural districts of the United States with electric circuits which should ultimately make it practicable to provide electric service to substantially all urban, suburban, and rural districts, wherever located; and excepting the possibility of some epoch making discovery, the creating of comprehensive consolidated systems of distribution appears to be the only way in which such a result can be accomplished.

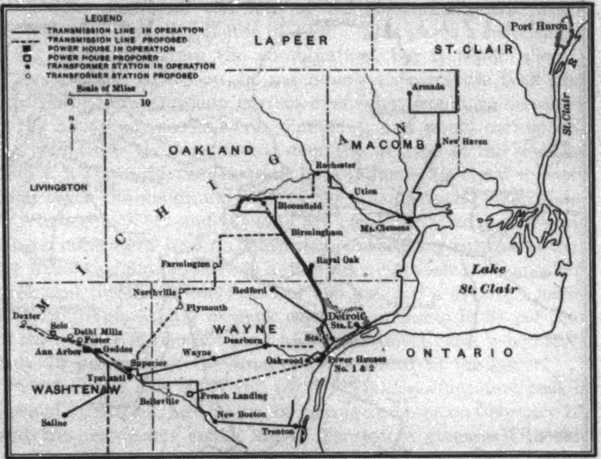
LEGEND
TRANSMISSION LINE IN OPERATION
TRANSMISSION LINE PROPOSED
POWER HOUSE IN OPERATION
POWER HOUSE PROPOSED
TRANSFORMER STATION IN OPERATION
TRANSFORMER STATION PROPOSED
Scale of Miles
0
5
10
N
LA PEER
ST. CLAIR
Port Huron
St. Clair R.
Armada
MACOMB
New Haven
OAKLAND
MICHIGAN
LIVINGSTON
Rochester
Utica
Bloomfield
Birmingham
Mt. Clemens
Royal Oak
Farmington
Lake St. Clair
Northville
Redford
Plymouth
Detroit
Sta. L
Sta.
Dexter
Scio
Delhi Mills
Foster
Ann Arbor
Geddes
WAYNE
Dearborn
Wayne
Oakwood
Power Houses No. 1 & 2
ONTARIO
Superior
Ypsilanti
WASHTENAW
Belleville
French Landing
New Boston
Trenton
Saline

Fig. 10.—Electric transmission lines of the Eastern Michigan Edison Company

Saving in Power House Equipment by Diversity Factor

The question of diversity factor as between various communities which are provided with electric service from a single transmission system is quite complex. By diversity factor is here meant the ratio of the sum of the maximum peak loads of separate plants which would serve the individual communities to the maximum peak load that would occur if the plants were combined. The condition may be illustrated by a consideration of the load curves of four central stations in the Northwest.

One of these, (Plant 1), serves a city of 50,000 inhabitants with mostly business and residence lighting service and has a maximum output of over 900 kw.; the second (Plant 2), serves a city of 20,000 inhabitants having a good lighting and commercial power load together with the local street railway service, and has a maximum output of 1250 kw.; the third, (Plant 3), serves an agricultural town of 4,000 inhabitants and has a maximum load of approximately 105 kw.; and the fourth, (Plant 4), provides only business lighting and power service, and has a maximum load of over 790 kw. These are highly dissimilar in their characteristics and give the following result as regards diversity factor:

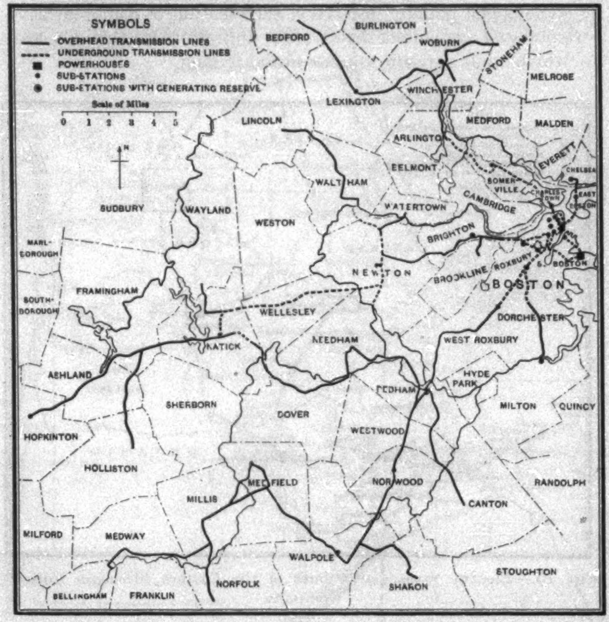
SYMBOLS
OVERHEAD TRANSMISSION LINES
UNDERGROUND TRANSMISSION LINES
POWERHOUSES
SUB-STATIONS
SUB-STATIONS WITH GENERATING RESERVE
Scale of Miles
0 1 2 3 4 5
N
BEDFORD
BURLINGTON
WOBURN
STONEHAM
MELROSE
WINCHESTER
LEXINGTON
LINCOLN
MEDFORD
MALDEN
ARLINGTON
EVERETT
CHELSEA
BELMONT
SOMERVILLE
CHARLESTOWN
EAST BOSTON
WALTHAM
CAMBRIDGE
WATERTOWN
SUDBURY
WAYLAND
WESTON
BRIGHTON
MARLBOROUGH
NEWTON
BROOKLINE
ROXBURY
S. BOSTON
BOSTON
FRAMINGHAM
SOUTHBOROUGH
WELLESLEY
DORCHESTER
NATICK
NEEDHAM
WEST ROXBURY
ASHLAND
HYDE PARK
DEDHAM
SHERBORN
DOVER
MILTON
QUINCY
HOPKINTON
WESTWOOD
HOLLISTON
MEDFIELD
NORWOOD
RANDOLPH
MILLIS
CANTON
MILFORD
MEDWAY
WALPOLE
NORFOLK
SHARON
STOUGHTON
BELLINGHAM
FRANKLIN

FIG. 11.—Electric transmission system of the Edison Electric Illuminating Company in Boston and vicinity

	Maximum individual peaks during the year			Largest coincident peak during the year		
	Kilowatts	Date	Time	Kilowatts	Date	Time
Plant (1)......	920	Jan. 22	8 p.m.	790	Dec. 23	5 p.m.
" (2)......	1250	Nov. 12	9 a.m.	1190	"	"
" (3)......	104	Nov. 15	6 p.m.	74	"	"
" (4)......	794	Dec. 27	5 p.m.	784	"	"
Total.........	3068			2838		

There is therefore a difference of 230 kw. between the largest coincident peak and the sum of the maximum peaks, which represents a diversity factor of 1.09. This seems a surprisingly small advantage from the combination, but it would allow a corresponding reduction in machinery to carry the peak load in a unified transmission system over what would be necessary if the maximum peaks were coincident, and would correspondingly improve the load factor over the average of the separate plants. The reduction in peak here indicated is equal to more than twice the maximum load of the smallest plant referred to.

When plants (1) and (2) only are combined, the time of their largest coincident peak is the same as in the foregoing case so that for these two plants there is a difference between the coincident peak and the maximum peaks of 190 kw. and a diversity factor of 1.10. This saving in peak capacity amounts to 21 per cent of the smaller maximum peak and a combined plant would have only 79 per cent of the smaller peak added to the larger.

Considering plants (1) and (3), the greatest coincident peak is formed by 920 kw. and 89 kw. occurring at 8 p.m. on February 19, and the maximum peaks are as heretofore given. With this combination there is a saving in peak capacity of 15 kw., which leaves the diversity factor little different from unity, but amounts to about 15 per cent of the peak output of the small plant.

When plant (3) is combined with plant (2) there is a saving in peak capacity of 51 kw. which amounts to 49 per cent of the maximum load of the small plant.

Two large groups of towns, for which the aggregates of maximum peaks are about 10,000 kw., show the following diversity factors: One of the groups, which comprises towns having rather uniform characteristics, shows a diversity factor of something over 1.10, while the other group, in which the towns have diversified business characteristics, shows a diversity factor which is larger than 1.18.

All of the data I have available tend to show that diversity factor as between towns is highly variable and in some cases may be large, while in others it may be relatively small.

Considering the first illustration presented, the saving in peak capacity arising from a combination of the plants might not cover the additional generating plant necessary to supply a reasonable maximum transmission loss. This, however, would be influenced by the number of power plants operated in the unified system, and their locations, as well as by the design of the transmission circuits.

In the case of the illustration of plants (2) and (3) and assuming that plant (2) is to be enlarged to supply both communities, with an accompanying abandonment of plant (3), there is then a saving in peak capacity of 51 kw. After allowing for the added generating plant required for the maximum loss in the transmission line to the smaller community, the saving in cost of equipment afforded by the diversity factor when making the enlargement of plant (2) amounts to between $5,000 and $7,500, which could be applied toward providing the transmission circuit. The power required for the small system could be generated at a low figure since about 50 per cent of its load would go to improve the load factor of the unified system without increasing the maximum load.

Referring to the last illustration mentioned above, there would be a saving in plant capacity on account of diversity factor of over 1800 kw., which, expressed in terms of investment, would amount to, say, $250,000. This can be considered as off-setting plant made necessary by a transmission system, since plant released from peak load service in a growing system stands in lieu of additions to capacity to take care of new business.

IMPROVED LOAD FACTOR

Improved load factor accompanies increased diversity factor since increase of the latter decreases the peak load without changing the average load. Referring to the next to the last illustration of diversity factor heretofore given, the weighted average of the annual load factors of the several towns may be taken as 22 per cent. Since the diversity factor between the towns is 1.10 the load factor for all of the towns served together will be 24.2 per cent, while if the diversity factor had been 1.18 as is the case in the succeeding example, the load factor would become 26 per cent. Thus for unified electric systems there is a saving in operating cost per kilowatt-hour owing to improved load factor as well as on account of the improved operating economies of larger generating plants.

The reduction of labor costs and the economy in consumption of fuel and supplies per unit of output for well considered large plants compared with small plants, is sufficiently recognized to make it unnecessary to consider instances here.

RELATIVE INVESTMENT PER KILOWATT OF CAPACITY IN LARGER COMPARED WITH SMALLER GENERATING STATIONS

The installation costs per kilowatt of electric generating plants are dependent upon so many variables, such as accessibility of location, character of foundations required, cost of land, quality of plant, labor saving devices installed, and efficiency, that it is not practicable to show specific relations between costs for larger plants as compared with smaller, but it is undoubtedly safe to say, in general, that the first cost of plant shows an advantage in favor of larger stations. In considering the investment in generating plants associated with unified electric systems, a disturbing factor enters in the form of power plants that must be discarded when local central station systems become absorbed in consolidated systems. But commonly such plants are absorbed into the more comprehensive systems on account of their inability to provide adequate service at low cost, so that the transmission companies often have sufficient leeway in the matter of rates to enable them to care for plant abandoned on these grounds.

The development of steam turbine generating units has an important bearing upon this matter. Some of the larger turbine stations have been built for less than $90 per kilowatt of rated output including all buildings, equipment and lands; and a detailed estimate for a very large plant has recently indicated that the total investment may go below $70 per kilowatt of rated capacity when suitable and well-located land of relatively low price is available for the station. These figures are to be compared with the usual costs of the older types of stations which have been from $110 to $170 per kilowatt of rated capacity. These improvements have come about with the advent of the steam turbo-generating unit as a commercial machine, but other forces have also played a part in the result.

SPARE EQUIPMENT

In general, as generating plants increase in size, or as two or more are brought into parallel operation, the percentage of spare capacity required to provide thoroughly reliable operation decreases, since one spare unit having a capacity equal to that which is eliminated by the disabling of any one of the generating units is sufficient either for one plant or for a combination of plants of ordinary capacities.

GENERAL MANAGEMENT AND OTHER GENERAL COSTS

The aggregates of salaries of officers, other general salaries including directors' allowances, and general office expenses for all of the electric companies of the Commonwealth of Massachusetts, as shown by the 1909 report of the Board of Gas and Electric Light Commissioners, are as follows:—

Salaries of officers	$234,853.03
Other general salaries, including directors' allowances	496,772.81
General Office expenses	307,443.54
	$1,039,069.38

In the general office expenses are included advertising, canvassing and engineering expenses.

The total expenses of operation, including taxes, legal expenses, insurance, bad debts, etc., for these companies aggregate, $6,279,046.26.

These figures show an average ratio of management expenses to total operating expenses for the electric companies in the Commonwealth of Massachusetts amounting to 16.5 per cent.

The ratio for larger electric companies may in some cases be less than for smaller companies, but in general the ratio seems to tend toward an increase as the companies become larger and more comprehensive. This is not surprising, since when companies reach large proportions it is possible for them to obtain the benefit of the services of technical and commercial men of the broadest and highest ability as their general officers, and to have a trained specialist at the head of each of their important departments. Thus a most efficient organization is obtained, composed of very capable men each having a single primary function in the organization as against the necessity existing in smaller companies of having one man directly responsible for many or all of the functions of the organization. By having such effective supervision of each department, the larger companies are enabled to make material savings by elimination of mistakes in general policies and in construction costs, and through taking advantage of all possibilities for reduction in operating costs by use of the most economical methods.

POSSIBILITY OF PROVIDING RURAL AND SUBURBAN SERVICE

I have included as one of the advantages obtained by consolidated and unified electric systems covering large territories, the ability to provide rural and suburban service that could not be profitably developed by local central stations. How large a factor this may become is difficult to predict, but that it is well worth careful consideration can not be doubted. While such service will provide valuable load, it will also place a company in position to give more comprehensive service, which should raise its standing in the estimation of the public.

When electric companies were originally organized, the product they had for sale was a luxury, consequently they were under little or no obligation to the general public. But electric lighting and power quickly became indispensable, and to-day if electric supply were discontinued it would seriously affect both the business and the recreations of all civilized countries. On this account, economists argue, responsibility now rests upon those providing electric service to manage their properties so that they will sustain an appropriate part in the affairs of business and recreation as well as earn satisfactory returns for the security holders. This involves the planning and operating of electric plants so that they may economically serve all who will be benefitted; and if the argument of economists is finally sustained by the judicial sense of the people, these plants will come into relations similar to those of common carriers, and must then serve all comers within reach, whether urban or rural.

SERVICE THAT IS TOO EXTENSIVE FOR SMALL COMPANIES

The immediately foregoing factor is closely related to this one. The electric lighting and power business in territories served by small central stations is seldom fully developed. This condition frequently enables a transmission company to enter a district with the certainty that a paying additional development can be made even though the existing service alone might not justify the extension.

Regardless of how small the fixed population of a community may be, an extended electric system which enters the territory is in position to provide service to consumers whether large or small. There are many instances where large power users are far from being practicable customers of small central stations, but which may be quite satisfactory customers of a comprehensive system. Some of these are purely summer users, such as stone quarries, stone crushing plants, and pumping plants for irrigation purposes; while in many cases mills and factories, whose power requirements are too great to be economically and reliably served from a local central station of ordinary capacity, may be admirably and profitably served by comprehensive transmission systems. It is likely that rural service will prove to be largely an off peak load since the power demand of an ordinary farm usually ceases at dusk.

A large company is usually in better position to obtain funds for large extensions than a small one, which gives it an advantage in being able to make additions to its system which would be impossible for the smaller company, and thereby to obtain business which is not within reach of the latter although it may be desirable for the community and profitable to the comprehensive company.

Probably one of the most important advantages which a strong, unified and comprehensive electric system possesses over a number of small separate supply companies serving a territory, lies in its ability to serve consumers profitably which the smaller companies are unable to serve. The advantages of the company with extended power lines are emphasized through the improvement of load factor which may be accomplished when the requirements of several cities affording good winter loads are associated with the power loads of industries which operate only in the summer.

The foregoing illustrations and arguments show that there are many elements tending to make the serving of large territories from unified electric systems an economic advantage; but it should be clearly borne in mind that success of such systems must depend upon making the advantages obtained offset the losses occasioned by the transmission circuits and apparatus, the cost of their upkeep, and the appropriate charges to depreciation and for extraordinary costs, together with a reasonable return on the added investment involved.

An illustration of what may be accomplished by a comprehensive electric system supported by good engineering skill is found in the case of an eastern municipality comprising a scattered population of about 30,000 inhabitants which was served by a local central station. This town became a unit in the distribution system of a large unified steam-electric system, by purchase of the local plant, and a careful estimate showed that the aggregate sum that the customers would pay per year, under the new conditions for service of equal amount and quality, would be about 18 per cent less than under rates required to net the purely local company a fair return on its investment after taking care of legitimate costs of operation. The service under the new conditions is manifestly of profit to the present supply company.

DISCUSSION ON "THE ADVANTAGE OF UNIFIED ELECTRIC SYSTEMS COVERING LARGE TERRITORIES." NEW YORK, FEBRUARY 10, 1911.

P. Junkersfeld: The author of the paper has summarized and pointed out many of the advantages of unified electric systems as compared to electric service by a considerable number of independent undertakings all in the same general territory. These advantages can undoubtedly all be realized to a greater or lesser extent. However, the ultimate success or failure of any such unified electric power system depends in very large measure upon four things:

1. The general character of the territory.
2. The cost of fuel and in some cases the availability of water power.
3. The conception, financing and design of such power system.
4. The management and development of the business.

In analyzing the character of the territory, we should consider such points as size and nearness to each other of towns and villages; growing or apparently stationary population and character of population; nearness to or isolation from some large city or metropolitan or industrial district and growth of such city or district; existing and prospective transportation facilities; tendency toward summer houses, summer resorts, amusement parks and interurban travel in any part of the territory; if the territory is agricultural, is there a tendency toward enlargement, or subdivision of farms, toward raising or fattening live stock, dairy farming or truck gardening. All of the above and other points that might be mentioned under this general heading have a material influence on the amount and combined load factor of the electricity that may be used for all purposes, and the economy with which it can be distributed.

The cost of fuel has a direct influence on the area that can be economically served by a unified electric system, and which is illustrated in several of the systems mentioned by the author in his paper. The plants serving individual or even two or three adjacent towns or villages are of necessity in most cases non-condensing steam plants, while unified systems are or would in most cases be served by condensing steam plants, and in some cases by water power or a combination of the two. The greater the cost of fuel, the greater the margin between cost of production in condensing and non-condensing plants, and hence the larger amount of investment in transmission conversion and distribution that would be justified. This in turn means a larger amount of business for the unified system and because of the increased quantity, better load factor and better diversity factor, a lower cost of production. The load factor and diversity depend upon the similarity of towns.

A high cost of fuel also means a greater probability that all industrial and commercial establishments will purchase the electricity they need from the unified system instead of some of them attempting to generate electricity in isolated plants on their own premises. This again makes for lower cost of production in the unified system. After an analysis of any given situation as to general character of territory and cost of fuel, if found to be favorable, it then becomes a question of experienced business and engineering judgment as to whether the time has come for a unified electric system and if so, how extensive it should be at the start, and for several years afterward. In arriving at such a decision, local conditions must obviously be taken into account, and also in many cases the market condition for the sale of securities. In this respect the unified system has a very great advantage over the small individual undertaking as was so well pointed out by such an eminent authority as Mr. F. A. Vanderlip, President of the National City Bank of New York, in his address of June, 1909, before the Atlantic City Convention of the National Electric Light Association.

The design, construction and extension of a unified electric system and the molding into such a system of many dissimilar local plants and systems, presents many problems requiring skill and experience. The generation transmission and conversion problems are most conspicuous, especially at the beginning of such an enterprise, and hence usually receive most attention. The necessity for equally careful attention to matters of distribution, and service to customers within individual towns or among adjacent towns or villages is very often not so well appreciated. If great care is not taken, the losses due to unproductive investment or inefficient arrangement, will be surprisingly large. This distribution engineering work not only at the start but continuously during the subsequent development and operation requires consistent good judgment and conscientious effort from day to day as a successful enterprise should keep on growing with the increase in population.

A unified electric system needs and can afford more skillful and experienced management than an individual plant.

In building up new business and in extending the service lines simultaneous experience in several different communities accumulates and which if taken full advantage of, means more rapid progress. In engineering, purchasing, construction and operation of the physical property, the advantages are beyond question.

The one thing most to be guarded against is the so-called " getting out of touch " with the various individual communities; in other words, not giving personal and prompt attention to requests and complaints and personal interest in and attention to the ambitions of the various localities. This, however, is largely a matter of getting and retaining a properly qualified representative for each locality. Moreover, this difficulty is not confined alone to unified electric systems.

There is one very great advantage in unified systems that was touched upon by the author, but which deserves further emphasis, namely the stability of the investment. It is the old story " in union there is strength ". A single town may prosper and flourish for a time and then suddenly recede and in some cases finally become almost depopulated. The investment in the electric plant has become practically worthless. Several such contingencies to a greater or lesser extent have occurred in different parts of this country. A multitude of towns and villages are not likely to all stop growing, much less to decrease in population. A decrease in population in one or more usually means a greater increase in the others, and the net result in the entire group in almost every part of this country is an increase in population and hence an increase in business.

Stability of investment or lesser risk means lower rate of interest. This means greater borrowing power and ability to get sufficient money for construction as substantial as the ultimate economy may indicate to be necessary and also for such extension to the system as the savings in operation or the income from the prospective new business may justify. As the fixed charges on the investment are the largest items in the yearly expenses it is especially important to have reasonably permanent construction and lowest total rate of interest.

The large majority of plants in small towns afford only a limited service, hence, do not fully develop their respective fields and very many end in a loss to the owner. There is abundant experience to indicate that unified systems with 24-hour service to all townspeople who desire it, and even to some farms located within reach of lines when properly developed and managed in territory which justifies such a unified system, results in better service and lower rates and greatly promotes the use of electricity and electrical supplies. In other words, unified electric systems in the present state of the art and under the favorable condition existing in many localities, are one of the economic necessities of the present day.

W. L. Robb: The thing that strikes me most in this paper is that most of the unified electric systems referred to are connected with hydroelectric developments; and a moment's consideration will show clearly why this is the case.

In the first place, there are relatively few strategic locations for hydroelectric development, and those strategic locations are fixed by nature. One can only locate such a development in a given locality. Another limitation we have in such work is that when we make such a development many of the parts of the system must be completely developed at the outset in order to make an economical installation. That means that the hydroelectric developments in the initial years of their operation, have a large amount of surplus power which absolutely goes to waste, and which cannot be conserved, and we can treat it entirely as a by-product proposition, and can afford, taking the entire system into consideration, to go into territories where a steam plant could never think of entering.

When we consider unified plants operated from central steam plants—there are many strategic locations to choose between—and we can also frequently make new strategic locations by building a small amount of railway. Furthermore, the extent of territory we can serve advantageously from a central system depends on the concentration of the population. A station 10,000 kilowatts capacity could operate much more economical than one of 500 kilowatts capacity; but when we compare a 10,000-kw. station with a 20,000-kw. station, we will find very little difference in the cost. Consequently, with concentrated population, we would not extend to the same distance that we do where there is less concentration.

I believe every public service corporation should supply everyone who wants the service if it can be done without a loss. Unified systems permit public service corporations to go into territories which could never be supplied by small stations. I think the small cities and towns should be considered under two heads—one of the heads being cities of 10,000 to 30,000 or 40,000 inhabitants, where we can operate a central station and earn dividends on the investment; and smaller towns, under 10,000 inhabitants, where it would be absolutely impossible to maintain a public service corporation and give a proper return on the investment.

When there is a unified system with a central station supplying a number of different towns and small cities, the small city gains a great advantage. It gets a better supply of electrical energy; it gets it during more hours of the day, and at lower cost to the consumer, with a given profit on the investment.

The small towns which could not support a public service corporation, can be supplied from such a station, and given good service at reasonable cost to the consumer. This benefits the town in two ways. If it is a residential town, it makes it more desirable to live in it, because we can get electric light in our homes. If it is a small manufacturing town, it makes it more desirable for the small manufacturer can buy power at the same rate as his competitor in larger towns.

I have studied the records of one of the companies in New England which began to spread out ten years ago. It is in a city with a population of 100,000 inhabitants, and during ten years that company has grown until it supplies electrical energy to ten smaller suburban towns, and all that is sold by two public service corporations in neighboring cities, and two municipalities. It has extende ten to twenty miles in each direction. A careful study of the accounts shows that the taking on of the business of these small towns has not materially affected the gross receipts of the company per capita in the territory served, nor has it materially affected the percentage of the gross receipts which are turned over as profits to the stockholders.

F. Darlington: There is one phase of this question that was very ably presented by Mr. Jackson a few months ago in Chicago, and although it is of great importance here, Mr. Jackson, from lack of space or from undue modesty, has not brought it forward to-night. I feel that it has a large bearing on unification of power plants. Mr. Jackson's Chicago paper was a discussion of " reserve funds, depreciation and obsolescence ".

It is the latter of these, namely, obsolescence, that has important bearing on the unification of power plants and it comes about in this way. We all know that electric companies that were started fifteen or more years ago, whether they were for lighting or for railroad or whatever purposes, have found a large part of the cost of conducting their business has been due to failure of apparatus to meet growing demands. It has not been that electric apparatus is generally worn out, but it has become obsolete, because new demands from year to year require larger and improved machinery. Electrical plants which were good when electric lighting first started were not good when business greatly increased in volume requiring larger generating plants and larger units of machinery. Then again, the electric lighting business was combined with larger electric power service, and this again, in many instances with electric railroading. The result in the past has been that the electric stations of fifteen or more years ago became obsolete because they could not do their work, and not because they were worn out, and so it is today with the electric plants of our smaller towns and villages, they are not worn out, but they are being replaced. They are becoming obsolete because large central power plants can do their work more cheaply.

How do centralized power plants meet these changing conditions? They are built for larger service and on a unit plan that can be economically extended to meet growing demands. It makes little difference to their operations whether a village is using electric light or mill power or interurban trolley power, as all a central plant has to do for additional service is to increase the size of its central station, that is to add generating units as required.

One gentleman this evening spoke of the desirability of getting the securities of electric properties so that they will be safe and pay a good return. The way to do this is to spend the money for plants which will be applicable to any condition that may arise, and we may confidently expect that in the future, as it has been in the past, the changing conditions will be toward larger plants and greater powers.

There is one other feature of to-night's paper of which I would like to speak, that is, the question of utilizing off-peak and secondary power. You all know what is meant by these terms. The off-peak power is what we might call the by-product of a central station, and Mr. Jackson has shown that if we take three or four or five or more villages and combine their service on one central station, the combined peak will be less than the sum of the individual peaks, but the combination will accomplish more than that. When we combine a number of services on one large plant we combine the off-peak capacities. If we have ten small separate power plants, each of these will have an off-peak capacity when the lighting or railroad or other work on each plant is not at its maximum demand, and this would result in a number of small supplies of off-peak or surplus power, and the separate utilization of the surplus power for each of the ten small stations would be difficult. Now, if you combine these ten stations into one large station, you will have one large supply of surplus power, and the problem of profitably using this is much more promising than it would be were it divided into ten small divisions, and this problem of utilizing off-peak power is finding its solution. Unfortunately, the time has not yet arrived when there is an unlimited market for such power, that is, power which is only available throughout certain hours of the day or night, or during certain weeks or months of the year, but it is a field in which there is excellent prospects of largely extending electrical applications.

There are several very promising methods in view for utilizing off-peak and secondary power. One is for electrochemical uses, and the most hopeful of these is the fixation of atmospheric nitrogen. This is an operation that can be shut down or turned on to accommodate other demands on the power plant, and when it is once established on an economical basis, it will afford a very wide field of profitable use for second class or off-peak power.

Another use that has not been generally made of off-peak power, but which undoubtedly will be greatly extended in the future is irrigation pumping, that is, the use of electrical power for lifting water for irrigating land. One or two electric plants have been put in in the West, almost exclusively for this work, and it has been found profitable, even where the cost of fuel is high, and where the power plants are costly, and pumping for irrigation should be very highly profitable where the off-peak or second class power of large central stations can be utilized. It is a kind of work that can be readily adapted to off-peak hours of operation. Wherever irrigation is carried out two methods suggest themselves. The first is by gravity, which is not always practical, and the second is by pumping and a few figures will show that a small amount of electric power will pump a vast amount of water. Allowing for all the losses in transmission and transformers, in electric motors and centrifugal pumps one kilowatt hour at the power house will lift one and one half acre-feet of water six and one-third feet in twenty four hours. This seems like a small amount of current for a large amount of work, but it is a figure that can be realized, and is based on a net efficiency of 40 per cent between the electrical output of the power house and the potential energy of the water delivered, and this has been realized by actual operations.

Now this means that if you are working in a country requiring one and one-half feet depth of water per year to irrigate land, 150 kw-hr. at the power house will lift enough water 40 ft. to irrigate one acre. Of course, 300 kw-hr. would lift the same amount of water 80 ft., and this means that if the electric power was charged for at one cent per kilowatt hour at the power house, or about 1.2 cents per kilowatt hour at the electric motor, the cost of electric power for irrigation would be only about $1.50 per acre per year, where the lift is 40 ft., and $3.00 per acre per year where the lift is 80 ft.

There is another possible use of electric off-peak power which has been indicated by very significant experiments in agriculture which seem to show that an electrostatic potential kept up on wires that are strung over land where growing crops are produced, stimulates vegetation and increases production. If this is once established and proved profitable, it means another tremendous field for electricity in agricultural districts and a convenient use for off-peak power.

To summarize briefly the foregoing; the unification of power plants and the building up of large central stations will enable electric properties to meet the growing demands of the future with greatly reduced losses due to obsolescence of machinery. The reduction of obsolescence will go far towards improving the securities invested in electrical enterprises, and increasing the earnings on the investment.

George H. Lukes: The author of the paper has analyzed very fully the several factors which often make it possible to substitute for disconnected systems, supplied from small local central stations, a unified transmission and distribution system supplied from a small number of relatively large central stations.

The success of such enterprises depends largely upon the character of the territory served. If the territory is of such a character as to render possible a considerable expansion of the business, either through rapidly increasing population or the development of power business, then the chances for the financial success of the enterprises are greatly increased. If, on the contrary, the territory is stationary in population, with no prospect for power business, the increase in fixed charges, (due to the large investment in transmission lines and substations) in some cases offsets any possible economies in operation. Our experience, however, shows that when a region is covered with a comprehensive distribution system, opportunities for increasing both power and lighting business often present themselves in territories which, at first sight, seemed barren. In other words, the presence of a supply often seems to create demand. As soon as it becomes generally known that power service can be obtained at a reasonable cost, little enterprises spring up here and there which apparently would not otherwise have come into existence.

Before taking up in detail some of the factors summarized on the first two pages of the paper, it might be well to refer to a very important point in connection with the management of district electricity supply companies, touched on in the third paragraph of the paper. The advantages of a centralized management are obvious. When, however, the system covers a considerable area and supplies service to a multitude of small cities and villages, it becomes more and more difficult to maintain that close relationship with municipal governing bodies and individual customers which contributes so much towards the financial success of the company. In order to overcome this difficulty it often seems advisable to have an organization which is neither purely functional nor district, but a combination of the two. In such an organization the local manager, or superintendent, is invested with considerable authority along certain lines, so that he can take immediate action to remedy undesirable conditions. Certain parts of the work, therefore, which might be performed more efficiently in the central office, are often delegated to the district offices, and this tends to offset somewhat the possible economies which might be obtained by centralized management.

The author finds after investigation that the diversity factor as between towns is highly variable and in some cases may be large while in others it may be relatively small. This is confirmed by our own experience. In many cases, however, it has been found that when a district supply scheme is substituted for disconnected distribution systems, the diversity factor increases, due to expansion of power business. This is particularly true in the case of the sale of electricity to electric railroads, which class of business is impracticable for small companies, but quite feasible in the case of larger companies.

In the consideration of the reduction in power generating cost due to larger plants and improved load factor, the author seems to have devoted most of his attention to the reduction in cost due to improved load factor. As a matter of fact, a reduction in generating cost often accompanies an increased output regardless of load factor; that is, in the same plant by increasing the output, at the expense of a decreased load factor, it is often possible to effect a considerable reduction in power generating costs.

Our experience confirms the author's statement regarding the possibility of providing rural and suburban service that could not be profitably developed by local central stations. In the case of one company supplying sixty towns and villages, careful examination has shown that not more than forty of these towns could afford to operate independent central stations with success. In other words, the consolidation of a number of small companies into a unified system has resulted in the extension of service to at least twenty, and probably thirty, towns which would otherwise be without the advantages of electric service. Referring to the question of 24-hour service which is invariably furnished by the district electricity supply system, it is very rarely possible for the small local central stations to furnish service more than from dusk to midnight, or at most from dusk to daylight. The furnishing of 24-hour service from a small local station would invariably make necessary a much larger investment and greatly increased maintenance and operating expenses. This condition in itself prohibits the supply of electricity for power purposes from the smaller local central stations. In the case of the sixty towns above referred to only one was giving 24-hour service prior to being absorbed by the district electricity supply company.

The question of whether or not district electricity supply companies, deriving their power from steam generating stations, can economically supply purely farming business is somewhat unsettled. The experience of the interurban railroad companies in supplying electric power to farms from their trolley lines seems to indicate that considerable business of this kind may be obtained. It is evident that many farming operations, such as pumping water, grinding feed, etc., might be easily performed by electric motors.

Many people are of the opinion that in the course of time the electric motor will largely supersede the gas engine in general use on farms within the territory of the district supplying systems. It is a question whether the general use of electricity on the farm will not be a strong factor in making farm life more attractive, and thus perhaps have a tendency to hold back the movement of population from the farms to the cities. These considerations lead up to the question of whether the time is not rapidly approaching when, as the author states, it will be the duty of the company supplying a given territory to furnish service not only to the cities, but to the rural communities. It naturally follows that if such is the case these district supply companies must be made in a measure independent of local municipalities, so that one part of a given territory cannot drive a hard bargain with the company at the expense of more remote and weaker communities.

Norman T. Wilcox: The whole trend of modern development is toward centralization and unification of effort; this because there are manifest advantages resulting both to the public and the people who furnish the funds for these enterprises.

If the work is well engineered, so as to increase efficiencies, reduce costs and give fuller and better service, and that of maximum efficiency, the enterprise is likely to be satisfactory; but, on the other hand, if the engineering is in the hands of inexperienced or otherwise incompetent engineers, the results may easily be disastrous and a disappointment to all concerned. It seems to me that the right kind of engineering is essential, even more essential than good management; because if the management is inefficient, we can often get rid of it at slight expense. On the other hand, bad engineering once fastened upon an enterprise is a permanent tax which once incurred cannot be avoided in the future.

In practically all of these unified enterprises, owing to the scope and complexity of the problems, the right kind of engineering is essential and should not be overlooked.

Philip Torchio: In the birds eye view the author gives of the existing conditions of electricity supply throughout the country and the analysis of the factors that are prompting these developments, we gather a true insight of coming events. This paper shows that centralization of power supply is economically advantageous to the welfare of large centers of population as well as to the most scattered districts. The analytical presentation of the eight reasons for this policy given in the paper brings out two fundamental facts; first, that multiplicity of small stations with unrelated management engender economical losses; and second, that such losses can be retrieved by concentration of power stations and concentration of management. It is the old saying, quoted by Mr. Junkersfeld, " in unity there is strength " to which should be added " in co-operation there is achievement ".

With these fundamental facts well established, there should be no hesitancy in the mind of all fair-minded people, be they engineers, financial men, public officials or private individuals, in lending their support to the advancement of the greater central station. Speaking as an engineer to electrical engineers either engaged in manufacturing or other pursuits, I will emphasize the fact that better opportunities and more business would be laid at our doors by the broad business policies of large central station managements than by the dwarfed developments of a multiplicity of small and unrelated systems.

If the time permitted it would be interesting to supplement the data given in the paper by detailed figures of the results obtained in specific instances by the policy of concentration. As a remarkable illustration I will only make comparison of the operation of the New York Edison Company supplying power to the Manhattan and Bronx Boroughs of Greater New York, and the operation of the London municipal and private undertakings, for the year 1909. The New York Edison Company had a total plant capacity of 173,100 kw. with a maximum load of 139,667 kw., all of the maximum load being generated at two main stations operated in parallel. The city of London with thirteen municipal undertakings and fourteen private companies, had a total plant capacity of 235,049 kw., and the sum of the yearly maxima of all the undertakings was 141,148 kw. From this comparison we see that the New York Edison Company had in 1909, 24 per cent spare capacity, while the City of London had 66 per cent spare capacity, which figure does not take account of the diversity factor of the twenty-seven different undertakings, which diversity factor would certainly have considerably reduced the contemporaneous maximum, thereby making the spare capacity still greater than 66 per cent.

I would like to say considerably more on the possible economies of unified systems operating in the same or contiguous territories, but the subject is too broad and the discussion would lead us away from the subject of this paper covering large territories. I think, however, that in Mr. Jackson's presentation of the hydraulic developments of electric transmission systems serving large territories, which illustration could be still more emphasized by developments in foreign countries, he has touched upon the essential truth that with cheap cost of power generation the central station can reach any market, almost regardless of distances. This refinement in production cost alone would influence directly only to a small degree the ultimate cost of power to the consumer in one locality, but it will indirectly enable the central station to extend its radius of activity, and by the general economies made possible by such unification of scattered districts the whole community will reap material advantages from such unifications.

The proper methods for the realization of these operating and investment economies are gradually becoming more and more recognized, principally through the efforts of a few men who have had the courage of their convictions and have ventured their capital in pioneering the development of the greater central station. While many obstacles are still in the way of the aims of these men, I do not think that the people of this country will overlook the great national economic benefits of this activity. It is only a few years ago that I gave utterance to a forecast of the future development of central stations, which forecast was at that time characterized as a poetic utterance, but now after listening to Mr. Jackson's paper and this discussion, it does not seem so nebulous and far from ultimate realization. I quote these remarks as follows:

" In closing this forecast, I would say that in the progress of the gradual uplifting of the industrial efficiency of the country, it is the province of the central station companies to furnish to the nation all of the power required by it in all commercial, industrial and agricultural needs. With thousands of central stations dotting the map of the United States, with a closely woven network of power wires connecting the heaviest centers to the most humble hamlets, is it not reasonable to expect that this wonderful organization should ultimately command and control within this territory the generation and distribution of power for everything that lights or heats, or operates machinery, or propels vehicles or trains?"

L. L. Elden: The author of the paper presented this evening has brought to our attention the favorable results of the unification of electric systems into larger organizations. In citing examples of successful combinations, reference has been made to the Boston Edison system with which I am connected. In confirmation of the author's conclusions as to the favorable results attained by the combined companies due to the diversity factor, I submit an analysis of the actual result in the Boston system based on the operation of the system in 1910. The system supplies 35 cities and towns by means of two generating and 28 substations. Considering the peak-day of 1910 in December and excluding transmission and conversion losses the ratio of the sum of the individual district peaks to their coincident peaks shows a diversity factor of 1.03 or as 38,000 to 37,000 kw. Considering the whole year's operation, this ratio is changed to 1.08 or as 40,000 to 37,000 kw. in favor of the combined system in each case.

The total losses in the transmission system and converting apparatus at the moment of the system peak aggregated 11,000 kw. equal to 23 per cent of the total generated kilowatts. Assuming the cost of the generating system at $125 per kilowatt, the total saving due to diversity factor is $125,000 while the increased investment necessary on account of losses is 11,000 kw., equal to $1,375,000, or a net increase of $1,250,000. This difference in investment must be included in capital account upon which dividends or other charges must be earned, a result which can only be obtained by an increased load factor on the generating station, more economical management of the combined system and the exercise of the highest executive and engineering ability as embodied in the controlling organization. One of the most serious problems before the larger company is the disposal of the discontinued generating equipment of the smaller companies in a manner which will not impair the financial interest of the controlling company, this apparatus usually standing on the books for original values, only a small fraction of which can be obtained when sold. Owing to these conditions, it is sometimes true that the generating apparatus maintained after consolidation is sometimes in excess of the capacity of that previously maintained by the several companies. This may be due to the introduction of larger and more economical units, and to the reluctance of the management to abandon perfectly good and modern apparatus which may be of value in emergencies or during peak loads. As an example of improvement in load factor on the main generating station due to the absorption of several companies into our system, an increase of 5 per cent was noted by an addition of business aggregating a kilowatt demand, approximately 1/15 of that previously observed.

The most important result of consolidation is the ability to serve large interests with practically unlimited amounts of power at rates and under conditions prohibitive in the smaller companies, due to lack of suitable apparatus and the inability to manufacture energy at less cost than the prospective consumer, conditions which are completely altered in the case of the combined companies.

Charles P. Steinmetz: I do not believe that there is a limit to the economical size of an electric generating system. While this opinion has frequently been expressed, and the economical limit placed at 10,000 or 20,000 kw. or even higher, yet the experience of recent years seems to contradict this, and to show that even with systems of 100,000 kw. capacity, an increase of the system leads to further economies. The 20,000 kw. units are more economical than 10,000 kw. and therefore a system using five, 20,000-kw. generators, is more economical than another using 10,000-kw. units. This means a system of 100,000 to 200,000 kw. total generator capacity, considering the number of units which are required to secure the economical use of units at all times.

There is no doubt in my mind that with an increased demand an increase of the system from several hundred thousand kilowatt to possibly millions of kilowatt will lead to still superior economies, if by no other means, at least by the fact that these very large systems can command the services of engineers which smaller systems cannot command.

Another subject is the utilization of spare power and off-peak power. I am interested in the data given on the power required for irrigation, and the relatively small amount of power it costs to operate a pumping plant for irrigation purposes.

Another use for off-peak power is the fixation of atmospheric nitrogen. We are rapidly approaching a time where we shall have to rely on fertilizers to maintain the productivity of our soil. Now the commercial production of nitrogen compounds by electrical power has been conducted successfully and economically; but only where the development of the water power has been extremely cheap, and where there was no market available for it—as for instance, in Scandinavia.

We must however realize that the main part of the cost of installation of such industrial operations is due to the plant needed to convert the very diluted nitric oxides into nitric acid, or solid nitrates for transportation; therefore a large part of the cost is due to the chemical side of the production.

When we come to intermittent use of the off-peak power, where the plant is used only for a part of the time, then the cost of the production rapidly increases, due to the interest on the investment, and we find, very soon a point is reached where the production of nitrates would not be economical, even if the power cost nothing. Herein consists at present the great difficulty of utilizing electrical power for the fixation of nitrogen. But since this results from the cost of concentration, then if we could use the fixed nitrogen in a highly diluted state, we could save most of the investment, and so materially reduce the cost; and it would be economical. That means that this method of using off-peak power lends itself nicely to the combination with irrigation. We might use electrical power for irrigation, and also for producing nitrates, and send out the nitrates as fertilizer with the irrigating water in a highly diluted state. In this way you could use a large amount of electrical power, and get the benefit of intermittent and off-peak power available in arid districts.

A Member: The author has presented some interesting facts in regard to this subject, and some of the speakers have supplemented that with the fact that in this distribution we should have good engineering and consider what territory the company should extend to.

Assuming a company located in a city of 40,000 people surrounded by towns of various sizes, under ordinary circumstances how long can it afford to make its extensions to reach these towns?

Suppose we had a town of 1,500 people? Could we afford to extend three miles to reach such a town, or ten miles, or how many miles? Suppose it was a village of 600 people, could the company extend three or six miles to such villages?

This is a very practical point, and in all of the talk to-night I have not heard a word as to just how far we could go to reach these various towns. I appreciate that it depends on the town itself—that is, whether there is manufacturing there, or what the conditions are; but this question of the cost of transmission lines seems to me a very important factor in this problem; and also, the cost of operating the substation. These questions seem to be more important than the question of what the power costs. But, assuming that additional power can be produced for one-half a cent per kilowatt-hour, how far can these lines be extended? The net work of the towns and the number of them, would of course affect it.

Wm. B. Jackson: There is just one point regarding which I will take a few moments to speak. During the discussion it has been suggested by several that most of the illustrations of unified systems I have presented relate to hydroelectric developments. This is true, and in a way indicates the fact that the number of important unified electric systems using water-generated power is at present much greater than the number of those using steam-generated power. This condition may be largely accounted for by the inherent character of most water-power developments which makes it necessary to have more or less important unified electric systems to make possible their profitable development. But I believe an element of large importance is found in the fact that our plant managers who are operating steam-electric plants have not, as a rule, had the courage or have not had the opportunity, to seriously attack the problem of building comprehensive systems. The facts show that, under suitable conditions, where ever the problem has been attacked with courage and with excellent engineering and commercial organizations, comprehensive steam-electric systems have grown and flourished. And to-day one finds scattered over all parts of the country steam-electric systems that are gradually working into unified systems in addition to those which have already become comprehensive in their scope.

It must therefore be expected that unified electric systems receiving power other than from hydroelectric developments will become relatively more and more numerous and important.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 14, 1911.

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HIGH-TENSION TESTING OF INSULATING MATERIALS

BY A. B. HENDRICKS, JR.

INTRODUCTION

Great accuracy in the high tension testing of insulating materials is not yet attainable, due to the variability of the materials, the difficulty of exactly controlling all the conditions of test, and in many cases, to the unreliability of the apparatus and methods employed.

The methods, results and conclusions of different investigators thus vary between wide limits and a close agreement between them is not to be anticipated.

There are exceptions to every statement that can be made regarding insulating materials. Those given herein represent the personal experience and opinions of the writer and are intended to apply to laboratory tests on small samples of commercial insulating materials only.

No attempt will be made to cover more than a few of the salient points, nor those which have already been thoroughly discussed, the latter including the testing of wires and cables, line insulators, and finished apparatus.

Tests. The tests under consideration are those for the determination of

1. Ultimate dielectric strength and arcing voltage.
2. Energy loss or dielectric hysteresis.
3. Specific capacity.

My own experience in the different departments of this field is very unequal, being confined chiefly to tests for dielectric strength and arcing voltage, but it will be of interest to consider also dielectric hysteresis and capacity.

TESTING APPARATUS

There are four main elements to be considered.

1. Alternating-current generator.
2. High-tension transformer.
3. Controlling apparatus.
4. Measuring apparatus.

Power Required. The results of tests for dielectric strength and arcing voltage will depend to some extent on the power and regulation of generator and transformer, and it may be considered necessary to reproduce exactly the conditions of a large power system in order that laboratory tests may give reliable data on the performance of the material when in actual use. This is hardly possible or desirable and it therefore becomes necessary to determine the requirements which must be fulfilled in order to obtain reliable results with apparatus of limited power.

It is necessary and sufficient that normal wave form and voltage be maintained, up to complete failure of test piece and the formation of a dynamic arc.

The critical, final moments of test are liable to be attended by high-frequency oscillations which sometimes form a complete flash over without leading to a dynamic arc. These oscillations have negligible influence on the voltage of normal frequency. till a flash over or momentary arc occurs, which may be attended by a sudden drop in voltage sufficient to prevent the formation of a continuous arc. It is at this point that the influence of the energy available becomes important, while previously it is of small consequence, the load being extremely small. The best that can be done is to provide apparatus of capacity sufficient to supply the small charging and leakage current and the energy absorbed by dielectric hysteresis, with the closest possible regulation and minimum distortion of wave form. By regulation is meant not only the voltage drop under continuous normal load but particularly the drop at the first instant of short circuit, or the capacity for instantaneous short-circuit current.

It is believed that the influence on results of the power of the testing apparatus has been somewhat exaggerated. For puncture tests (as distinguished from arcing tests) on small test pieces and particularly on oil, and for measurements of dielectric hysteresis and specific capacity, reliable results, comparable to those obtained in actual practice, may be obtained with very small generators and transformers. These must be well designed and of characteristics especially adapting them to this use.

For all of the tests under consideration the power and current required are usually very small though the power factor may be low. It is, therefore, entirely feasible to provide apparatus of much greater volt ampere capacity than will normally be required, thus insuring close regulation and minimum distortion of wave form.

GENERATOR

Generators of the distributed field type have the essential characteristics and are now available in sizes suitable for laboratory work. These machines of high speed and distributed field and armature windings not only give an almost perfect sine wave at all loads and power factors but deliver very high energy at instant of rupture of the dielectric; that is, they have great capacity for instantaneous short circuit current, due to low armature impedance.

Ordinary revolving-field machines of distributed armature winding but non-distributed field winding, may give a sine wave at no-load but are liable to produce distorted waves with higher harmonics of considerable magnitude under small loads of low power factor, such as is represented by the core loss of transformer and capacity current of test piece, and are thus less suitable for this work. The armature impedance is high, hence the capacity to deliver great energy at instant of short circuit is also limited.

Small Generator. It is evident that a small generator with capacity for maintaining the voltage wave normal for a few cycles at the critical moment of rupture will give results approximating those on a large power system, where considerable impedance intervenes between generator and point of breakdown.

Excellent results may be obtained with smooth-core alternators of the old Thomson-Houston pattern. These are now obsolete but may be obtained at very small cost of the dealers in second hand apparatus.

The wave form of these machines is an almost perfect sine, their chief limitation being poor regulation. Nevertheless they are on the whole very satisfactory and most of the results given herewith were obtained with them.

Examples. A steam turbine generator of the distributed-field type is shown in Fig. 1, and the wave form in Fig. 2. The illustrations and waves represent a 25-cycle, two-pole machine, but it is believed that at 60 cycles, 4-pole, the wave form would be equally as good. The field winding would then occupy 34 slots, resembling a direct-current armature.

A Thomson-Houston generator is shown in Fig. 3, and the wave form under load, while testing a high-tension transformer terminal at 69,300 volts, is shown in Fig. 4. The transformer used is similar to that shown in Fig. 5, the terminal under test being connected between one terminal of transformer and the grounded neutral point. The oscillograph was connected directly across the 69,300-volt terminals in series with a non-inductive resistance consisting of glass tubes filled with distilled water.

The potential wave shown is in almost perfect agreement with a mathematical sine wave.

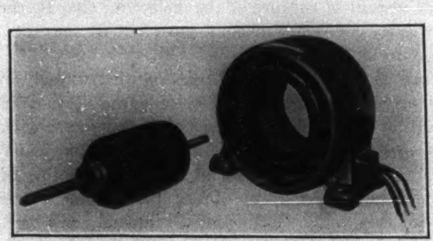

FIG. 1.—Sine-wave generator—distributed field type. 37.5 kw — three-phase—25 cycles

TRANSFORMER

Capacity. There has been a good deal of misapprehension in connection with the question of transformer capacity. It has been usual to specify a certain minimum kilowatt capacity for a given voltage, regardless of the other characteristics of the transformer, not realizing that such a specification is indefinite. The rating of these transformers is more or less arbitrary and elastic, as with a given design but slight changes are necessary in order to halve or double the nominal capacity as stamped on the name plate.

The space occupied by the copper as well as the loss therein, is very small, hence the current rating could easily be changed to this extent, with negligible influence on the rest of the design. It is not the rating stamped on the name plate that determines the energy in the discharge circuit but the regulation, particularly as expressed by the impedance voltage, which has thus to be taken into account.

In the tests under consideration the conditions are always at one of the extremes of small load or dead short circuit, except for an instant immediately preceding breakdown. Thus the reactance is of chief importance.

In specifying transformer capacity there should then be expressed the kilowatt rating, and the resistance and reactance voltages at full load, the kilowatt capacity being of interest only as a basis for determining regulation.

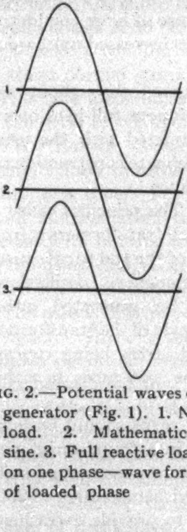

FIG. 2.—Potential waves of generator (Fig. 1). 1. No load. 2. Mathematical sine. 3. Full reactive load on one phase—wave form of loaded phase

FIG. 3.—Thomson-Houston smooth core alternator—35 kw.—single- phase—125 cycles

Fortunately there is no difficulty in obtaining very high kilowatt capacity with close regulation. The secret of the best designs of high-tension testing transformers lies in the use of extremely massive cores, few turns in the winding, and reinforced insulation of the end turns. By these means the poor regulation of the transformer and the great liability of the end turns to short circuit have been overcome.

Many transformers for this work have been designed simply as large induction coils with closed magnetic circuits. The small cores employed necessitate a very large number of turns in the high-tension winding, which is objectionable for two reasons; the winding becomes delicate and bulky, and the reactance, being proportional to the square of the number of turns, is very high. It is much better to increase the cross-section of core and the volts per turn, as the core is not liable to break down and the reduced size of winding may be better insulated and in every way made more substantial and reliable. Modern designs therefore operate at 5 to 20 volts per turn instead of 1 to 3 as formerly.

The small number of turns renders the use of large conductors permissible, which is also of advantage from increased mechanical strength and less danger of open circuits.

Thus the transformer should be designed throughout as a *power transformer* and preferably for continuous full-load operation, as contrasted with the usual bulky and delicate constructions of large impedance.

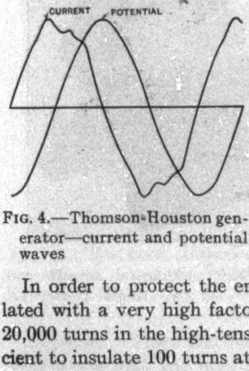

FIG. 4.—Thomson-Houston generator—current and potential waves

Failures. The principal cause of failure of such transformers is from short circuit of the end turns caused by high-frequency oscillations. These may be generated either outside or inside of the transformer, the resultant stress being concentrated on the end turns in either case.

In order to protect the end coils a few turns should be insulated with a very high factor of safety. In a transformer with 20,000 turns in the high-tension winding, it has been found sufficient to insulate 100 turns at each end to withstand 1000 to 2000 times normal voltage between turns, and to provide extra insulation between the end coils and the rest of the series.

In addition, a choke coil without iron core should be connected to each terminal, external to the transformer.

Double Voltage Test. By the standardization rules of the A.I.E.E. testing transformers are required to stand double normal high-tension voltage between high-tension winding and low-tension winding and iron, for one minute.

For all ordinary purposes this is an excessive and unnecessary requirement as it subjects the insulation throughout to four times the maximum strain normally applied to the terminals only, thus demanding maximum insulation for middle point of winding the same as for the ends, though in practice this point can never be subjected to more than half voltage.

The transformer may be built to stand such strains, but at a great sacrifice in size, cost and operating constants, and nothing of real value is to be gained by such designs.

There is little danger of breakdown to low-tension winding or iron, failure usually being due to short circuit of the end turns by high-frequency oscillations.

A better and more rational method of test is to apply an induced voltage of 50 per cent above normal, the middle or end of high-tension winding being grounded. This in effect applies 2¼ times normal strain throughout, and is ample.

It is here assumed that the *strain* is proportional to the *square* of the *stress* or voltage.

Time Rating; Cooling. In addition there should be a time rating. Such transformers seldom operate for more than a few hours at a time. For the lower voltages, where the losses are small and radiating surface of tank ample, there may be no necessity for limiting the time of continuous operation, especially as the usual designs are extremely large for the capacity, compared with ordinary power transformers.

The case is different when voltage is high and the design more compact. There is then insufficient radiating surface for continuous operation (more than ten hours) and artificial cooling must be resorted to. It has also been found that the heating effect of the loss in the insulation must be taken into account. Negligible at low temperatures, as for one hour operation, this loss may equal the core loss after ten hours run, increasing very rapidly with the temperature, accompanied by a great decrease in the dielectric strength of the insulation, and consequent danger of breakdown.

Thus it becomes of the highest importance to keep the temperature as low as possible, much lower than for ordinary designs, as thereby the problem of insulation is much simplified.

By using a more bulky design, providing great radiating surface, and a higher factor of safety in the insulation, the necessity for limiting the time of operation, and for artificial cooling, may be eliminated. As result therefrom, the size, weight, cost, core loss, and impedance will be greatly increased.

Grounded Neutral. A great gain may be effected by normal operation with middle point of high-tension winding permanently grounded. For the majority of laboratory tests there is no good reason why this connection should not be used. Thereby the stress is reduced one-half and the major insulation about three-fourths at one stroke, resulting in greatly reduced size of transformer and much better electrical constants throughout. Grounding is also necessary in order to make use of voltmeter, ammeter and wattmeter at center of high tension winding as described under "Measurements."

The ground connection may be made so as to be readily broken without dismantling the transformer, so that tests may be made with either terminal grounded or free if necessary.

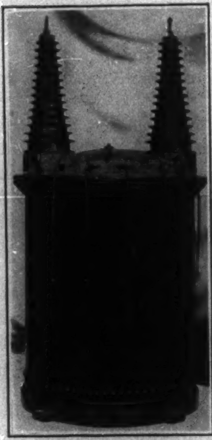

FIG. 5.—100-kw., 200,000-volt testing transformer — with grounded neutral

The advantages of the grounded neutral are very great as it results in a radical reduction of size, and improvement in efficiency and regulation.

One of the transformers used in the present investigations is shown in Figs. 5 to 7 and has the following characteristics.

100 kw., 60 cycles, 2000 to 200,000 volts

Volts per turn	10
Impedance voltage	7 per cent
Resistance voltage	1 per cent
Regulation—unity power factor	1.25 per cent
Tank—height	52 in.
Tank—diameter	44 in.

Neutral point of high tension winding is grounded.

Figs. 8 to 10 represent a standard type of high-tension transformer of large capacity designed for factory tests of line insulators. In this also the neutral point of high-tension winding is grounded.

CONTROLLING APPARATUS

The voltage must be varied through a wide range in a perfectly regular manner without breaks or steps. To effect this many different methods are in use, but generator field control is by far the best for laboratory work.

Field Rheostat. This should be designed to vary the generator voltage in a perfectly continuous manner or in very small steps, and the generator should always be operated at excitation as near normal as possible, for the sake of close regulation and good wave form.

Multiple Windings. Either the generator or the low-tension winding of the transformer should be wound with four parallel circuits. These may be connected in all necessary combinations by means of series parallel switches, cylinder controllers, or terminal boards with movable links.

The last named method is inconvenient in use; series parallel switches are simple and satisfactory, but the cylinder controller is least liable to lead to mistakes, and is quickest in action and therefore best.

Four parallel circuits on the low-tension side of the transformer have been found ample, and are more readily provided than on the generator. This gives 25, 50 and 100 per cent transformer voltage at normal generator voltage. The latter may be varied from 50 per cent to normal voltage, thus giving a range of 12½ to 100 per cent transformer voltage. If a greater range is required it should be provided by a suitable transformer.

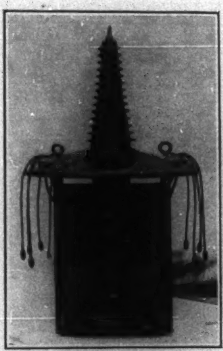

FIG. 6.—100-kw., 200,000-volt testing transformer—interior side view—showing voltmeter coil at center of high tension winding

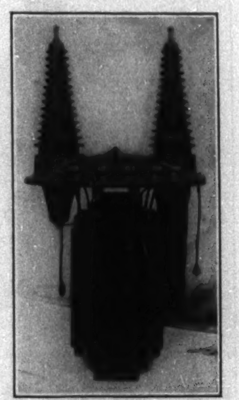

FIG. 7.—100-kw., 200,000-volt testing transformer—interior end view.

Taps on High or Low-tension Winding. These should not be used and are unnecessary when four low tension coils are provided.

Taps are always hard to insulate, and if on the high-tension side also necessitate a separate terminal insulator for each tap. Extra insulation of coils adjacent to taps is required, the same as on end coils unless the winding is in two parts with taps near the center not used for terminals. These inside connections are difficult to bring out and properly insulate and their use requires handling of the high-tension circuit. Multiple high-tension windings are objectionable for the same reasons.

Multiple Transformer Units. A number of transformers of comparatively low voltage may be connected in series to obtain any desired total voltage. As each unit must be insulated to stand the voltage due to its position in the series, nothing is to be gained by this arrangement.

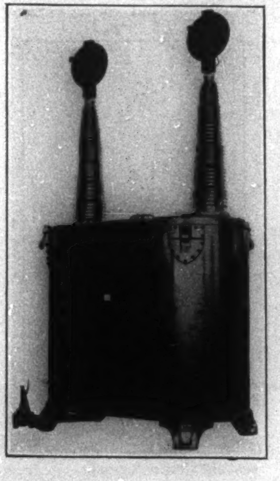

FIG. 8.—250-kw., 400,000-volt testing transformer—with grounded neutral

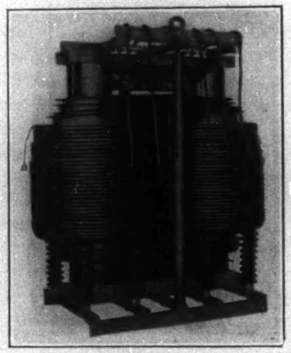

FIG. 9.—250-kw., 400,000-volt testing transformer—interior view

Intermediate insulating transformers may be inserted, but add to the complication and are otherwise disadvantageous.

Since transformers are now available of capacities up to 500,000 volts or more in a single unit, there remains little reason for the use of multiple units, or for more than two at most.

MEASURING APPARATUS

VOLTAGE MEASUREMENTS

Opinions differ widely as to the best method of determining the voltage of the discharge circuit. As this is by far the most important, and in most cases the only measurement made it should receive the most careful consideration.

Spark Gaps. For certain special measurements this is the only method that can be used. It is however liable to be the source of errors and trouble.

Its use is authorized by the A.I.E.E. standardization rules and therefore, quite commonly insisted on, although in the opinion of many experimenters the device is not as reliable as desirable.

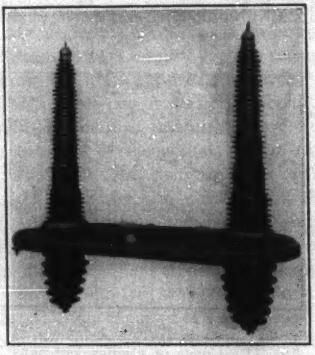

FIG. 10.—250-kw., 400,000-volt testing transformer cover and high-tension terminals

It is my desire to have the A.I.E.E. reopen the question of the proper method of measuring testing voltages, to further investigate the limitations of the spark gap and consider the use of the method I have found most satisfactory, namely the voltmeter coil on transformer core.

It has been stated by Fisher (International Electric Congress, St. Louis, 1904) that the use of large disks back of needle points gives more regular results. My own experience with this arrangement has not been thorough enough to warrant definite conclusions, but it would seem to be, in general, subject to the same criticisms as the plain needle point gap.

It has also been claimed that spherical electrodes are superior to needles, but there is the added labor of frequent refinishing or replacement of the balls.

Fig. 11 represents the results obtained with needles and ½-in. (12.7 mm.) balls under identical conditions using a sine-wave generator Fig. 3 and a 50,000-volt transformer quite similar to Fig. 5, the spark gap being connected direct to transformer terminals, and the voltage controlled by series parallel switches and field rheostat. The results with needles and with balls seem fairly definite, but it is extremely doubtful whether they would remain constant if any of the conditions were changed.

The spark gap is only an indirect means of determining voltage. It is generally used to find the voltmeter setting for a definite gap when a specified voltage is to be applied to test piece or to measure an unknown voltage by successive trials with different settings.

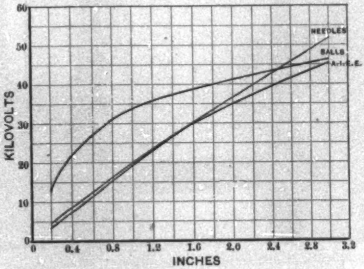

FIG. 11.—Curve of needles and balls

In either case great accuracy is not possible and the method is tedious in application. Errors may be introduced by the fact that conditions may not be the same during the spark gap trials and the actual test, since the test piece and gap may not be connected in parallel.

To limit the current and oscillations, resistances of about one ohm per volt are specified to be used in series with the spark gap, and may introduce a disturbing element.

As principal causes of variation in sparking tests may be considered:

Variation in wave form.
Transient voltages.
Growth of charge in the circuit.
Ionization of air.

Variation in Fundamental Wave Form. Spark gap voltages are proportional to maximum values of potential wave and the stress in the dielectric is also proportional thereto. We are, therefore, interested in the effective voltage only as a measure of the maximum voltage, and it is this fact that is largely responsible for the use of the spark gap. If, however, the testing apparatus including generator, transformer, and controlling devices, is properly designed and operated, a sine wave of potential in the discharge circuit may be assured, and measurement of effective values will then be sufficient.

Transient Voltages. It is not, however, variation in wave of fundamental frequency that is the chief disturbing factor, but transient voltages generated by the unstable condition of the test circuit. In most cases, these are of limited power and duration and have negligible effect on the dielectric unless high-frequency oscillations across a spark gap are set up. Transient voltages may jump the spark gap without starting dynamic arcs but setting up high-frequency oscillations of considerable power and destructive effect, or may establish an arc and would then be taken as a measure of the actual voltage of fundamental frequency. Thus it is seen that transient voltages are of negligible effect in the absence of a spark gap, but with spark gap connected, with or without test piece in parallel, may give misleading indications of the actual maximum of normal frequency voltage, and consequent stress in the test piece, or cause abnormal stresses by high-frequency oscillations.

Growth of Charge. The capacity of a condenser varies with the frequency, depending on character of dielectric and becoming less as frequency increases, due to absorption.

It has been observed during high tension tests that the charge seems to increase with time at constant voltage and frequency, and that at irregular intervals a critical point is reached, causing flash over and high frequency discharges at spark gap in parallel, or at some weak point in the test piece.

This can occur without causing a dynamic current to follow, and the length of spark gap is then not a measure of the normal frequency high-tension voltage. If the voltage is raised very rapidly it may be carried past the point of high-frequency discharge, and a genuine arc produced at the spark gap at a normal frequency voltage corresponding to its length, and considerably in excess of that first observed. This second higher voltage is then taken as the correct one.

Example. A high non-inductive resistance in parallel with spark gap and test piece tends to prevent abnormal rise in voltage. The following results were noted in testing three high tension transformer terminals in parallel each covered with tinfoil and thus having considerable capacity. The generator shown in Fig. 3 and a transformer similar to Fig. 5 were used. Resistance consisted of glass tubes filled with distilled water. Effective voltage by conversion ratio = 69300, corresponding to 5.6 in. (142 mm.) by A.I.E.E. spark gap curve.

Conditions	Voltage by spark gap
Spark gap alone	86000
Spark gap and resistance in parallel	73800
Spark gap and terminals in parallel	84000
Spark gap, terminals, and resistance in parallel	79000

Each voltage is the average of five to seven trials, the arcing distance being determined by first setting voltage by voltmeter and then closing gap till breakdown occurs.

As seen, the longest gap is broken with spark gap alone connected, and the shortest with resistance alone. Current in resistance is 0.05 ampere or one-tenth full load on transformer. Core loss is about 1200 watts; current taken by terminals is 0.03 ampere.

This example shows the variation that may occur between different trials under identical conditions, and also those due to slight changes in conditions.

Wave forms of voltage and current of test circuit are shown in Fig. 4. For taking voltage wave, the oscillograph was connected in series with the water resistance.

The average variation of spark gap voltage from conversion voltage is plus 4500 to 16700 volts, or a maximum of 23.3 per cent.

The maximum individual variations are from minus 4800 to plus 18200 volts, or a maximum of plus 26.2 per cent.

The spark gap undoubtedly gives fairly accurate measurements of the maximum instantaneous voltage except possibly for very high-frequency oscillations of small energy. As ordinarily used, however, its indications are interpreted as representing the effective value of a sine wave having a maximum value corresponding to the spark length. As the spark length depends on the maximum instantaneous voltage only, this may lead to large errors.

In the example given the effective values of the voltage must have been nearly the same throughout, the oscillations which broke the spark gap being of too high a frequency to have much influence on effective values. As given, however, the figures represent effective values and thus give a very misleading idea of the actual conditions.

Ionization of Air. Ionization of the air will also affect the indications of the spark gaps. This will depend on circumstances as time of application of stress, form and arrangement of high-tension circuit, amount of air circulation, etc.

Conclusions. The chief arguments for the spark gap which, as I believe, have lead to its adoption by the A.I.E.E. are, that it measures the maximum potential and that in many cases no better method is available.

For laboratory purposes in connection with ordinary tests on small test pieces, which are alone under consideration, it should be easily possible to provide a sine wave generator and a transformer of close regulation, thus eliminating the need for the spark gap.

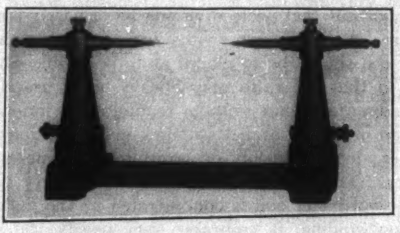

FIG. 12.—5-inch, 50,000-volt needle point spark gap with carborundum resistances in pillars

Voltmeter Coil in High-Tension Transformer. This I consider the most nearly perfect method for determining the high tension voltage with convenience and accuracy. All that is required is a coil of few turns inserted symmetrically at middle of high-tension winding and connected thereto at the neutral point. A few turns of the regular winding could be used, but for mechanical reasons it is better to use a separate coil.

Connection of the windings is imperative, as it is not practicable to insulate the voltmeter coil against half the high-tension voltage, as is necessary if not connected.

Taps should be brought out at 25 per cent and 50 per cent of voltmeter coil winding to give convenient voltmeter readings at one fourth, one half and full potential.

Ratio of High Tension Voltage to Instrument Reading. It would seem superfluous to specify that this ratio should for the sake of convenience and accuracy be a simple number except for the fact that a most awkward multiplier is generally used as 50,000 to 110=454; 20,000 to 550=36.36; 10,000 to 108=92.6, etc.

The ratio in these cases should be

50,000 to 100=500 or 0.5 kilovolts per volt.
20,000 to 100=200 or 0.2 kilovolts per volt.
10,000 to 100=100 or 0.1 kilovolts per volt.

This arrangement eliminates mistakes and is more convenient than a chart or the slide rule.

The voltmeter should be dead beat. Magnetic damping of dynamometer types is satisfactory, but hot wire instruments have been found by me very convenient and reliable.

It is important that scale divisions be of nearly equal length throughout. A three-point switch for connecting the taps in voltmeter coil should be so placed as to be visible when taking readings, so that the ratio may always be accurately known. It is an advantage that voltage readings are independent of the position of series parallel switches on low-tension side of the transformer, depending only on position of voltmeter switch.

Accuracy. The accuracy of this method is very great. Although the voltmeter coil is concentrated at the middle of the high-tension winding, it embraces very nearly the same flux as the main winding. Therefore, the voltmeter readings are almost independent of the transformer reactance or ordinary variations in load and power factor.

The low-tension winding of the transformer Fig. 5, 6, and 7 consists of a cylinder closely surrounding the core. The high-tension winding is composed of a series of thin multi-layer coils with few turns per layer and arranged concentric with the low-tension coil. The voltmeter coil is similar to the high-tension coils and is inserted at the middle of the series and connected thereto.

MEASUREMENT OF ENERGY LOSS OR DIELECTRIC HYSTERESIS

With increasing potentials, the energy loss in the insulation, or " dielectric hysteresis " is becoming more and more a factor that must be taken into account in the design of high-tension apparatus. Its accurate determination is always difficult and frequently impossible, because of its small magnitude and the high voltage and low power factor involved.

Wattmeter in Low Tension Circuit. This requires accurate determination of losses in the high-tension transformer itself, which must be subtracted from all readings. With generator and transformer of proper design, with low exciting current and core loss in transformer, fairly good results are possible if the loss to be measured is large. All determinations of voltage and frequency must be extremely exact or large errors are introduced, as the losses to be determined are usually much smaller than the transformer losses. An additional difficulty is found in the change of wave form and core loss, due to load in the high-tension circuit, so that the transformer losses are not the same when loaded as when unloaded and the exact amount to subtract is uncertain.

Wattmeter in High Tension Grounded Circuit. This method, suggested by Dr. Steinmetz has been used with very satisfactory results. The series coil of a wattmeter is inserted directly into the high-tension circuit, preferably at the grounded neutral point, the winding being cut and the terminals brought out for this purpose. The potential coil of the wattmeter may be connected across a few turns of winding at the neutral point, or preferably to the voltmeter coil. Low reading commercial instruments are suitable for fairly large losses and the reflecting dynamometer for small losses.

To avoid danger from accidental open-circuiting of the high-tension winding at the neutral point, a short-circuiting device should be placed across the series coil of the wattmeter, connected as close to the transformer as possible. Two flat springs, may be used, pressed together and separated by thin paper, which punctures at about 500 volts.

Cathode-ray Power Indicator. This most elegant method, recently devised by Professor H. J. Ryan, appears to be superior to all others, especially for small measurements at high voltages. I have not yet had the pleasure of using it but purpose to make a practical trial immediately, as it is undoubtedly of great value in all high tension investigations.

SPECIFIC CAPACITY

The methods commonly used require standard condensers for comparison, the Wheatstone bridge, ballistic galvanometers, large test pieces, etc., and do not duplicate actual working conditions.

Great accuracy is not required, since the constants of materials vary over a wide range and the approximate average values on commercial materials are sufficient for the present purposes.

These determinations are easily made by a reflecting dynamometer ammeter inserted directly in the high-tension winding at grounded neutral point, and measuring sine wave current at normal frequency, the advantage of the method being that it determines the capacity of small test pieces under normal conditions, and is simple and direct.

Published results are of little more than academic interest since they do not represent commercial materials nor conditions, and apparently the constants of greatest value to the designer have never heretofore been measured.

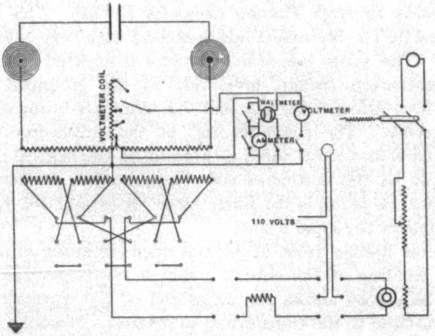

Fig. 13.—Arrangement and connections of apparatus for all high-tension tests

The complete arrangement for measurements of dielectric strength, arcing voltage, energy loss, and specific capacity, which I have found satisfactory is shown in diagram Fig. 13.

Cylinder controllers or switches for series parallel connection of four circuits are no doubt generally well known, but are also shown diagrammatically in Fig. 14 for the reason that I have never seen them published.

The following elements are shown in Fig. 13.

1. Exciter.
2. Field switch; normally held open by means of a spring, for the sake of safety.
3. Generator field rheostat; this should preferably be motor driven, so as to vary the high-tension voltage at a uniform rate.

4. Main switch, with auxiliary contact for lighting a red lamp as a danger signal; this may be arranged to illuminate voltmeter, for tests in the dark.

5. Automatic circuit breaker.

6. Series parallel switches on low tension side of transformers.

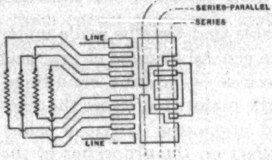

FIG. 14.—Series-parallel controller for four low-tension coils in transformer

7. Four low-tension coils of transformer, grounded.

8. High-tension winding of transformer, with loop brought out at grounded center for wattmeter and ammeter; short circuiting device for loop.

9. Voltmeter coil connected to high-tension winding at grounded center, and provided with taps and voltmeter switch.

10. Choke coils and testing terminals or electrodes.

11. Voltmeter, ammeter, and wattmeter connected for all measurements.

METHODS OF TEST—MATERIALS—TESTING DEVICES

GENERAL METHOD

Conditions of Test. To obtain exact and definite results all the conditions of test must be accurately known to the smallest detail. As, in general, the results of test are desired simply to show the value of the material under actual working conditions which naturally are variable and indefinite, it becomes necessary to adopt a standard, and as nearly as possible, a simple ideal method, which may be relied upon to give comparative results, and will permit easy and clear mathematical treatment.

The previous history of test piece, its precise condition, its form, size, and thickness, form and intensity of electrostatic field, temperature, time, frequency, and whether tested in air or under oil, may all have great influence on the results and must be taken into account.

Preparation of Test Piece. Since the presence of water is the greatest source of variation in the electrical qualities of insulating materials, it is necessary that all that are liable to absorb water should be thoroughly dried and waterproofed before testing. Liquids are best dried by filtering through dry blotting paper in a filter press.

Special tests require special treatment and testing devices, which may be different for each case, hence will not be further considered here, though the above general principles apply to these also.

Standard tests, however, should be standardized in every particular, including the testing devices, and I here purpose to describe some of the methods, test pieces, and testing devices which I have found satisfactory.

Range of Conditions. It is desirable that tests be made under normal conditions, representing the general average of practical use, and also under the two extremes or limiting conditions, particularly of temperature, as in the majority of cases the temperature of operation of insulated apparatus, covers a wider range and with greater resultant effect on the properties of the insulating material, than any other single variable.

Temperature. High tension apparatus may operate over a temperature range of 150 deg. cent., or from −25 to +125 deg. cent., the lower limit being found in oil switches and similar apparatus generating little heat and located out of doors, and the upper limit in steam turbine generators and transformers operating at overload in heated power stations. These are the extreme conditions, and to represent standard practice, tests might be made at three temperatures as follows:

25 deg. cent. representing normal room temperature.

65 deg. cent. representing normal temperature rise of 40 deg. cent.

100 deg. cent. representing upper limit for transformers and turbine generators.

Heretofore the initial temperature of the test piece only has been considered. The heating effect of the stress, depending on the duration of test, and its results, varying with the facilities for heat dissipation, have a vital influence on the results of test and are extremely difficult to control and allow for. The above considerations apply equally to tests for dielectric strength, arcing voltage, hysteresis and specific capacity.

TIME

Test for Dielectric Strength and Arcing Voltage. The results will largely depend on the time of application of stress in all materials which exhibit an energy loss and consequent heating. The loss may be due to dielectric hysteresis as in solid organic compounds, to conduction as in all materials containing traces of water, and in the most general case to both.

If free from water, dielectric hysteresis alone need be considered. This is greatest in solids and least in liquids, viscous materials occupying a position midway between the two.

In general the puncture voltage will decrease with increase of time of application of stress, and it then becomes necessary to determine the complete time-versus-puncture-voltage curve.

Such curves show wide variations for different materials and often for the same material, or for any slight change in the conditions of test, and must be interpreted with the greatest care.

It is necessary, however, to have some basis for comparison and the following methods have been used and are recommended.

Instantaneous Tests. Voltage is applied beginning with a low value, not over one half of puncture voltage, and raised slowly and steadily till puncture occurs.

The total time occupied obviously varies somewhat but should be at a rate permitting voltage to be read to an accuracy of about 1 per cent of final voltage.

This method is suitable only for comparative results where great accuracy is not required, and is more particularly adapted to transformer oil and thin sheet insulation. Heating effects are negligible.

One Minute Tests. This method should be used for the majority of all tests. It is a step by step method, the voltage as before being applied at a low value, held constant for one minute, then increased slowly by a small percentage, again held constant for one minute and so on till puncture occurs. Heating effect may be considerable.

The initial voltage should be about 75 per cent of the puncture voltage, and the increments about 5 per cent each, the aim being to continue the test for three to five minutes.

Time Tests. Beginning with the instantaneous test, successive tests are made at decreasing voltages, each being maintained constant till puncture occurs, the curve being continued till the voltage approaches a constant value. Heating effect may be very marked and have a most important influence on results.

Test for Arcing Voltage. Results will not be greatly affected by time of test, except as this determines the temperature and consequently the specific capacity.

Tests should be made somewhat as in the " one minute test ", each voltage being maintained till the effects become sensibly constant, the final increment of voltage being very gradual.

Test for Energy Loss. The time of application of stress affects the energy loss principally as it influences the temperature of test piece. For complete information it is necessary therefore, to determine the curves of energy loss versus both time and temperature, at or between the limits of 25 and 100 deg. cent.

Test for Specific Capacity. The considerations of the last paragraph apply equally to tests of capacity.

FREQUENCY

The range of commercial frequencies—25 to 60 cycles—is too limited to have great influence on the results in standard tests and heretofore I believe it has not been customary to make any difference in the insulation of apparatus for variations in operating frequency over this range.

Test for Dielectric Strength. Results will vary slightly with the frequency but principally due to variation in energy loss and consequent heating, the higher frequency leading to a lower puncture voltage.

Test for Arcing Voltage. Results will vary with frequency, as this determines the charging current, and to a large extent, the "static" discharges and creeping effects. No great difference is to be expected between 25 and 60 cycles, however, and tests should be made at 60 cycles, so that results may be on the safe side.

Test for Dielectric Hysteresis. Results will depend on frequency and it may be necessary to make tests at both 25 and 60 cycles.

Test for Specific Capacity. Results will scarcely be affected by a variation in frequency between 25 and 60 cycles, the lower frequency tending to give higher values of capacity due to absorption.

Measurements by the proposed method may more readily be made at higher frequency, such as 120 cycles, since a small condenser will then take a current of sufficient magnitude for accurate measurement on ordinary instruments.

Greater accuracy would also be made possible by the use of the familiar guard ring.

Great refinement in method is unnecessary in the present state of the art, particularly as the variations in different samples of commercial materials are sufficient to entirely mask small errors in method.

Conclusions. Tests for dielectric strength of materials for use at 25 to 60 cycles should be made at the frequency of 60 cycles. Such errors as exist due to variation from normal frequency are negligible or on the safe side.

For exact determination of dielectric hysteresis and arcing voltage the normal frequency must be used, and for capacity measurements 60 to 120 cycles is suitable.

Test piece should be considerably larger than electrodes to avoid leakage at edges of disks, and measurements should ordinarily be made under oil to avoid corona and leakage, and to represent condition of actual use of the dielectric as in oil-filled apparatus.

TESTING DEVICES—FORM OF ELECTRODES—EFFECT OF EDGES

Theoretically the edges of electrodes should be rounded to a large radius to avoid the increase of dielectric flux density due to sharp edges. However there is always question regarding what this radius should be and in the absence of standards, I have generally used *square*, but not *sharp* edges, the corners being rounded to an insensible radius.

Thin sheets such as varnished cloth, whether tested in air or oil, seem usually to puncture at the edges of electrodes unless the latter are well rounded. Hence, I have used rounded edge terminals for standard tests, but square edges for special tests on greater thicknesses or under oil.

The increased stress on corners of electrodes is, however, objectionable, and in consequence thereof, failure of the dielectric tends to occur at this point. It is my intention to adopt electrodes with corners rounded to a radius equal to one tenth of the diameter of the flat face, for all standard tests for dielectric strength of flat sheets and plates.

Insulating Medium. All tests must be made either in air or under transformer oil and often in both ways, the results usually being quite different for the two cases. Obviously the conditions of test should as closely as possible resemble those of actual use, the best method to adopt depending on circumstances.

Insulating materials for high tension work are generally used under oil, and tests in air are impracticable owing to liability of arcing around the test piece, unless the latter is very large. The effects of immersion may be briefly discussed.

Effect on Test Piece. The electrical properties of insulating materials permeable to the oil are in general improved by impregnation and they should therefore, be thoroughly saturated before testing.

If the properties in a normal unimpregnated condition are required tests must be made in air, or immediately after immersion, or the material may first be rendered oil proof by a thin coating of lacquer or similar material of negligible influence on the other properties.

The good effect of saturation will largely be lost if test is made in air as the stress will drive the oil out of the material to some extent. This is especially noticeable with oiled pressboard, one of the best known insulators, in which the dielectric strength is nearly twice as great under oil as in air.

In laminated materials, the filling of the interstices with oil will also have an influence on results.

Effect on Electrostatic Field. The general effect of oil immersion is to eliminate corona and static discharges over the surface of test piece, to render the form and intensity of electrostatic field more definite and uniform and to concentrate it at edges of electrodes.

Effect of Temperature. This is very marked and consequently of great importance, especially in long time tests, a large volume of oil tending to maintain a constant temperature through out.

Tests at the different standard temperatures are thus readily made under oil, the oil being brought to the desired temperature before making test.

MATERIAL

Form. The material under test will usually be in one of the following forms: (1) liquids, (2) thin sheets and flat plates, (3) tubes, (4) miscellaneous.

Size. The puncture voltage of insulating materials depends more or less on the size of the area under stress, since the larger the area the greater the chance of including abnormally weak spots; therefore, this area should be as large as can conveniently be used.

Thickness. The thickness of commercial insulating materials usually lies between 0.001 in. and 2 in. (0.0254 and 50.8 mm.) and by far the greater proportion between 0.01 and 0.5 in. (0.254 and 12.7 mm.). Tests are most often required on single layers and multiple layers up to a total thickness of 0.5 in. (12.7 mm.)

The dielectric strength in general varies between the square root and first power of the thickness, for either single or multiple layers, hence, unless the law of variation is accurately known, the test must be made on the actual thickness under consideration.

Thin Sheets. Flat circular disks of various diameters with square or rounded edges are generally used as electrodes.

It is usually most convenient to test very thin sheets in air, and for this purpose the material may be placed horizontally between the ends of brass cylinders of suitable diameter and weight, the lower cylinder being of any convenient height and the upper one made heavy enough to flatten out slight bends in the sheet and make uniform contact. The larger the area of the electrodes the better, but the dimensions are limited by practical considerations, it often being necessary to make a large number of trials on a small sample.

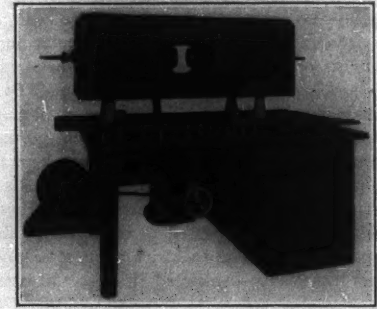

Fig. 15.—Spark gap for all high tension tests—showing different forms of electrodes employed and motor driven oil pump

For my own work there have been used brass cylinders 2 in. (50.8 mm.) in diameter with edges rounded to $\frac{1}{4}$ in. (6.35 mm.) radius, the lower cylinder being 1 in. (25.4 mm.) high and the upper about 5 in. (127 mm.) giving a pressure of 2 lb. per sq. in. (0.14 kg. per sq. cm.) area of face. These as well as a smaller pair are shown in Fig. 15 at the left end of table.

For standard tests of varnished cloth in single layers the upper electrode is used with a $\frac{1}{8}$-in. (3.1-mm.) brass plate 1 ft. (0.3 m.) square for the lower electrode, five or ten trials being made, the upper electrode being shifted for each trial.

Flat Plates: Spark Gap for Tests in Air or Oil. The apparatus shown in Fig. 15 is used for a great variety of standard and special tests on all kinds of test pieces, in air or oil, hot or cold, and also for special tests on the oil itself, up to 200,000 volts.

The testing box contains three compartments, the testing compartment at center being provided with plate glass windows in each side, and smaller oil-filled compartments at each end, the latter serving merely to support and insulate the terminal rods.

The latter are 0.75 in. (19 mm.) in diameter, graduated in 20ths of an inch and sliding through heavy brass tubes supported in the ends and partitions of box. Graduated screw collars on ends of tubes permit measurement of distance between electrodes to 0.01 in. (0.25 mm.)

The inner ends of rods are drilled for needles, and a large number of electrodes of different sizes and shapes are also furnished and arranged to slip over the ends of rods.

These are shown on the table in front of test box. The large disks at the right are 10 in. (25.4 cm.) in diameter and are used for measurements of specific capacity. Flat disks with square (not sharp) edges are provided of 1, 2 and 4 in. (2.54, 5.08 and 10.16 cm.) diameter, the latter being shown in position on the rods, and generally used when size of test piece permits.

The end compartments of the box are always kept filled with oil, while the middle or testing compartment, is filled as required from the storage tank beneath, by means of the motor-driven centrifugal pump, shown connected to the box by rubber hose. The opening of a valve in this pipe, with pump stationary, allows the oil to flow by gravity backward through the pump to the storage tank.

For high temperature tests, the oil is heated by means of small electric heating units immersed in the oil.

This outfit is very complete and extremely convenient, nearly all of the results of tests given under " Characteristics of Insulating Materials ", being obtained with it.

Tubes. Insulating tubes must usually be tested under oil between a central conductor and an outside wrapping of heavy lead foil. Paper, varnished cloth, treated tape and similar materials may be conveniently tested when wrapped to the required thickness on round rods or tubes, and handled the same as tubes.

Results will obviously depend on the ratio of outside to inside diameter of insulation, the ratio for least maximum dielectric flux density for a given outside diameter being, as is well known, theoretically equal to $e=2.718$.

If this ratio closely approaches unity the results will be comparable to those for flat disk electrodes, hence a diameter of

2 in. (5.08 cm.) for the rod or tube, with a thickness of 0.125 to 0.5 in. (3.17 to 12.7 mm.) for the insulation, are suitable proportions.

In my own work, rods of rectangular cross-section 0.5 in. (12.7 mm.) by 1.5 in. (38.1 mm.) (resembling the proportions of armature coils) and round rods 0.75 in. (19.05 mm.) diameter have generally been used, but brass tubes of 2 in. (50.8 mm.) outside diameter and 3/32-in. (2.38 mm.) walls have recently been adopted, and are recommended for standard tests.

Miscellaneous Shapes. Definite specifications can not be given for special tests, but the general considerations already given may be applied, the aim being to obtain either *ideal* or *working* conditions, as the case seems to demand.

Tests for Dielectric Hysteresis. My own experience with these tests is very limited and no method has yet been standardized, but the methods recommended with the spark gap and tubes would seem to be suitable.

Test for Specific Capacity. The large electrodes shown in Fig. 15 are used for these measurements, a voltage of 5,000 to 15,000 at 60 to 120 cycles on test pieces 0.125 to 0.250 in. (3.17 to 6.35 mm.) thick giving good readings on reflecting dynamometer. Still larger electrodes would be advantageous if the size of the testing box would permit.

Liquids. Transformer oil is by far the most important liquid to be tested and as the same device may be used equally well for nearly all liquids, the spark gap for oil testing need alone be considered.

This consists of an insulating containing vessel of small capacity, provided with suitable electrodes which may or may not be adjustable for arcing distance.

Ordinarily a constant distance is used so that all results may be directly comparable and a standard dielectric strength specified for the oil.

Three forms of spark gap are now in use:

Electrodes arranged vertically in cup.

Electrodes arranged horizontally in cup.

Electrodes arranged horizontally on separate frame dipping in cup.

The electrodes consist of balls, flat disks or a ball and disk. All are adjustable for arcing distance, although a constant distance of 0.15 or 0.20 in. (0.59 or 0.78 mm.) is generally used rendering adjustment unnecessary.

Quantity of oil required for test is from a pint to a quart

(0.47 to 0.94 liters), a number of trials being made on each sample (usually five) and average taken, the oil being stirred between successive trials.

The disadvantages of these types for rapid work in a testing laboratory are:

1. Adjustability is in most cases unnecessary.
2. A large sample of oil is required for test.
3. A number of trials must be made on one sample. The arcs have a serious effect on the dielectric strength of sample, tending to increase it by the burning out and driving off of impurities or to reduce it by carbonization of oil. Hence the first trial only is reliable. Each trial should be made on a separate portion of the oil.

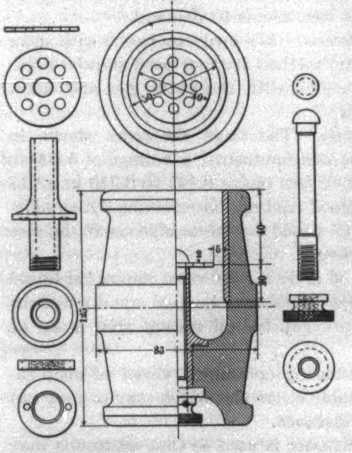

FIG. 16.—Proposed spark gap for oil testing—thin disk and tube model

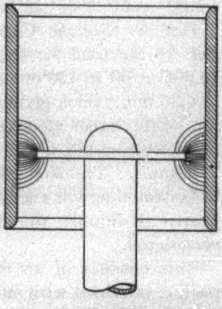

FIG. 17.—Proposed spark gap for oil testing—electrostatic field of thin disk and tube model

4. Distance between electrodes frequently is too small for accurate determination and maintenance.
5. Construction is not adapted to rapid and convenient use.
6. Voltage required is inconveniently high, 50,000 volts or more, necessitating large and expensive transformers.

In my own work it is often necessary to make five trials on each of 100 to 200 samples per day, hence the necessity for rapid manipulation is obvious.

I have designed about fifteen different forms of spark gaps, seven of which have been built and tested. The final form is intended to overcome most of the above objections and is shown in half section in Fig. 16, which also exhibits the seven component parts. It consists of a hard rubber cup, the upper portion containing a brass tube lining as one electrode, and the lower supporting a brass column carrying at its upper end a brass disk concentric with the tube and forming the other electrode. All dimensions are in millimeters.

Inside diameter of tube.................=50 mm.
Diameter of disk.......................=40 mm.
Thickness of disk......................=2 mm.
Length of gap..........................=5 mm. = 0.1968 in.

Edges of the disk are square and eight holes are drilled through it to allow free oil circulation and prevent the collection of air bubbles underneath.

The considerations underlying this design are as follows:

Voltage. This can only be reduced to a convenient value by reducing the arcing distance, or by increasing the density of the electrostatic field by concentrating it at one electrode.

An error of 0.001 in. in 0.2 in. (0.025 mm. in 5.08 mm.) equals one-half per cent, hence 0.2 in. (5.08 mm.) is as small a gap as is desirable. It is also a standard in wide use. It therefore, becomes necessary to resort to a concentrated field.

Shape of Electrodes. The disk and tube seem to combine some desirable features:

1. Both electrodes are of simple symmetrical form easily made and measured and of great durability under use.

2. Disks of one and two mm. thickness with square or slightly rounded corners all gave the same results, hence slight variations in thickness of disk and condition of edge may be neglected.

3. The ratio; volume of oil under stress to total volume is very great.

4. The slight burning of the electrodes shows that arcing occurs over a zone about 15 to 20 mm. wide on the tube and 2 to 3 mm. back from edge of disk. This is somewhat surprising, as it would naturally be thought that arcing would always occur from the edge of disk, and especially from the corners.

This is not the case but arcing occurs anywhere within the limits above given, showing the great lack of homogeneity of the oil.

The effective area of the tube electrode is thus represented by a band 15 mm. in width and 157 mm. in length or 24 sq. cm. which is far greater than in any other proposed form of spark gap.

5. The cup and terminals are circular and thus perfectly symmetrical about a vertical axis.

6. There are no corners to retain dirt and it is easily kept clean. The hard rubber gives practically perfect insulation, is non-absorbent and neutral to the oil.

7. The voltage required is about 75 per cent of that for 0.2 in. (5.08 mm.) between 0.5 in. (12.7 mm.) disks, varying with the quality of the oil, as shown in Fig. 18 which gives the corresponding voltages for the two forms of spark gap. A 60,000-volt transformer is necessary with the standard gap of 0.2 in. (5.08 mm.) between 0.5-in. (12.7-mm.) disks, or 45,000 volts for the disk and tube gap.

8. No adjustment is needed, and as every part is circular in form, it is easily made and accurately set.

Method of Use. The spark gap is not provided with terminal connections but is intended to be slipped into a simple supporting frame, making contact by spring clips. For most convenient use it may be mounted on trunnions, and arranged to be inverted for emptying into a vessel beneath, automatically connecting to the spring clips when in a normal position.

A very small sample (155 cu. cm.) may be tested, but ordinarily only one trial should be made on each filling, the cup being filled and emptied for each shot. One quart (0.94 liters) of oil is sufficient for 7 trials. This assures that a normal representative sample is used for each trial. The sample should be thoroughly mixed immediately before pouring into the spark gap, as the impurities rapidly settle to the bottom, and care should be taken to eliminate air bubbles before testing.

The instantaneous method of test is always used though the results are affected in an irregular way by the time element. Apparently this is not due to dielectric hysteresis, but to transient voltages in discharge circuit, and to circulation of the oil in the cup, which eventually carries the impurities between the electrodes and tends to give lower readings of dielectric strength with increase of time.

I have not thoroughly investigated this point and it is possible that better results would be given by one minute tests but the regular adoption of this method is out of the question owing to the time and labor involved. Better results should also be obtained with less effort by repeating the test on additional samples.

Results. This spark gap has been thoroughly tested in comparison with a standard which consists of a wooden box holding about one quart (0.94 liter) of oil, and provided with flat disk electrodes arranged horizontally in box, the disks being 0.5 in. (12.7 mm.) in diameter and placed 0.2 in. (5.08 mm.) apart, five trials made on each sample of oil.

The comparative results are shown by the curve of Fig. 18.

It must be admitted that for the higher voltages the disk and tube gap is not so sensitive to variations in quality of oil as is the double disk gap. This objection can be overcome by the use of a disk 1 cm. in thickness instead of 2 mm., with corners square, or rounded to 2 mm. radius, which gives the same sensitiveness as the standard double disk gap. This unfortunately sacrifices the advantages of the lower voltage required in testing, which was one of the main objects of the new design, but apparently a uniform field is required for sensitiveness in indications of the quality of oil.

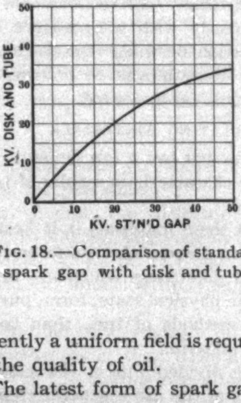

Fig. 18.—Comparison of standard spark gap with disk and tube

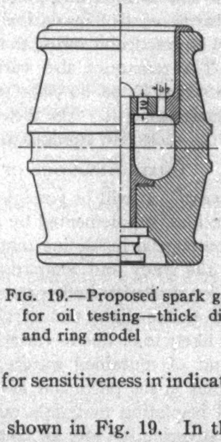

Fig. 19.—Proposed spark gap for oil testing—thick disk and ring model

The latest form of spark gap is shown in Fig. 19. In this a disk one cm. thick with square (not sharp) corners is used with a flat ring of one cm. width of face as the outer electrode, thus giving a nearly uniform field but requiring the same voltage as the double disk gap.

With this construction the volume of oil under test is still greater than with the thin disk, and the intensity of the electrostatic field is more nearly uniform. There seems to be no good method for greatly reducing the voltage required without loss of sensitiveness.

Accuracy. It must be admitted that no great accuracy can be attained in oil testing, owing to the great variation in purity of the oil itself in different parts of the same sample or tank.

Variations of 50 per cent for successive shots on the same sample are common, and in general, the average of five trials cannot be considered accurate to within less than 10 per cent plus or minus. As already explained this may be due not so much to inaccuracy of method as to real differences in different portions of the oil itself, but it is none the less difficult to determine a definite value for the dielectric strength of a quantity of oil. If it is of extreme purity, successive tests (average of five shots each) may agree within 1000 volts.

Other Methods. The use of a small induction coil has been proposed in place of the transformer. I have not thoroughly tested this method and doubt its effectiveness.

Measurement of insulation resistance has also been tried but found impracticable owing to the extremely high resistance of the oil. The resistance also varies greatly with temperature and there seems to be no close connection between resistance and dielectric strength. The dielectric strength must be known, and it is the dielectric strength that must be measured.

Characteristics of Insulating Materials

General. It will be possible to present but a few general considerations, supplemented by some characteristic results of tests on commercial insulating materials.

In the study and comparison of these materials it is best to look for similarity and correspondence everywhere, rather than to emphasize slight and accidental differences which are much more likely to be due to variations in physical state, form, purity, amount of contained water, and methods of test, than to be inherent in the particular *kind* of material.

All insulating materials may be divided into a few classes, each covering broadly all materials of the same general characteristics, and if the group to which a given material belongs is known, its behavior as an insulator may often be predicted.

The literature of the subject is incomplete and unsatisfactory, the problem usually being attacked from the standpoint of physics rather than from that of engineering, and every investigator using different materials and methods.

Classification

The materials with which we are most concerned may be divided into the three chief classes, *viz.*, liquid insulators, viscous insulators, and solid insulators; and obviously many materials may exist in any of these states.

Liquids. Fessenden states that "Practically all the fluids which are not simple elements, like mercury, have very high ohmic resistance, and all have practically about the same dielectric strength."

This agrees with my own experience, as I have always found approximately the same dielectric strength in all transformer oils, gasoline, benzine, cylinder oil, linseed oil, varnish, etc., if at normal air temperature and equally pure and free from water. Since it is practically impossible to determine the *exact* dielectric strength of a liquid, any characteristic difference would be difficult to detect if small, minute traces of water, which are generally present, having a far greater effect on the results than the difference in *kind* of liquid. Fine dust and dirt in suspension has a very deleterious effect on the oil, comparable to that of water in reducing the dielectric strength.

Carbon tetrachloride (CCl_4) has been suggested as a substitute for transformer oil, but is a very powerful solvent, and as such, may attack insulating materials, so that it is difficult to maintain its purity under use. Its dielectric strength, if pure, equals that of transformer oil, but it is rapidly reduced by arcing, each successive breakdown test giving lower results than the preceding.

In general, the dielectric strength of all insulating liquids at 25 to 100 deg. cent. equals 50,000 volts (for 0.2 in. or 5.08 mm. between 0.5-in. or 12.7-mm. disks) plus or minus 10,000 volts, depending almost entirely on the amount of contained water and dirt.

The dielectric strength of transformer oil when frozen *hard* is much greater than when liquid, and reaches its lowest value when in the viscous transition state between a liquid and solid.

The curve Fig. 21 represents the effect of water on the dielectric strength of oil when thoroughly mixed. It is probable that the reduction of voltage is here a maximum, and that the effect would be less serious if the oil and water were less thoroughly mixed.

The mixture was allowed to stand about five minutes after mixing and before testing to allow air bubbles to rise to the surface. Tests on dry oil, shaken and allowed to stand as specified, showed that the effect of air bubbles, if present, was negligible.

I have not yet measured the dielectric hysteresis of liquids but it is undoubtedly very low. The specific capacity of transformer oil has been found sensibly constant and equal to 2.5.

Viscous Insulators. In this class may be placed such materials as vaseline, mixtures of transformer oil with rosin, asphalt, etc., which seem to have the same dielectric strength as transformer oil.

Varnish may exist in a partly dried viscous condition on the inside of finished apparatus, and when in this state seems to possess the same dielectric strength at 20 deg. cent and 85 deg. cent. although when thoroughly dried, the dielectric strength is much reduced by the higher temperature.

In general, I have found the dielectric strength of viscous insulators, to be less than that of the same material in the dried or solid state, but to be unaffected by a rise in temperature from 20 to 85 deg. cent., apparently due to lower energy loss from dielectric hysteresis.

The dielectric hysteresis and specific capacity have not been measured but are probably between those for liquids and solid insulators. The results of long time tests under high voltage show great variations in heating, which may be due to the presence of water or other impurities.

Solid Insulators: Variations. These exhibit greater variations than either liquids or viscous materials, and also possess much greater dielectric strength, dielectric hysteresis and specific capacity.

Thickness. These variations are found not only between fundamentally different materials but also between different *thicknesses* of the same material. For example, pressboard is made in all thicknesses from 0.007 to 0.125 in. (0.177 to 3.17 mm.) the thinner sheets being much denser, harder and more highly finished than the thick, and the variations in dielectric strength between the different thicknesses may be as great as between entirely different materials. Practically, they *are* different materials mechanically, though made of the same stock and in the same manner.

These considerations also apply to many other materials.

Fibrous Materials: Treatment. Cloth, tape, paper, pressboard, wood, and to a smaller extent the chemical hard fibers, such as leatheroid, rawhide, and vulcanized fiber, can hardly be classed as insulators at all until they have been dried, and coated or impregnated with an insulating varnish or compound which fills the pores and renders the surface waterproof. Hence nothing need be said regarding these materials in the undried and untreated state.

Hard Fibers. The chemical fibers are impervious to insulating liquids or compounds but freely absorb water. When dry they are fairly good insulators but to remain so must be immediately waterproofed.

Surface Coatings. A surface coating of insulating varnish increases the dielectric strength but slightly, unless the thickness of coat is large compared to thickness of material or the latter is a poor dielectric. This is shown in the case of varnished pressboard.

Color. Vulcanized fiber and many other solid insulators are commonly colored with bone black or iron oxide. The dielectric strength seems to be unaffected by either, contrary to the usual impression. Lamp black is a conductor and its use is fatal to insulation.

Hardness and Density. In general, the dielectric strength of fibrous materials increases with the hardness and density.

Wood. Hard wood thoroughly dried and impregnated with an insulating liquid or compound is an excellent insulator. Maple is considered best, but equally as good results have been obtained with cherry, ash and yellow pine.

For impregnation, transformer oil, paraffine and rosin have been used, depending on the use to be made of the wood, the oil treatment being suitable for wood to be used under oil, and paraffine or rosin if used in air.

Paper. Treated paper forms a large part of the insulation of high tension apparatus, particularly of transformers.

Parchment, horn fiber, and pressboard, are three of the best and most widely used, and in conjunction with mica, varnished-cloth, tape, and treated wood form the major part of the entire insulation.

Pressboard. The major insulation of all high-tension transformers consists of pressboard, either varnished or boiled in transformer oil. The latter simple and obvious method, seems to be a recent discovery, but one of great value as thereby the dielectric strength is increased above that of almost any other known material. It is particularly high for very short-time tests, a point of great importance where excessive transient voltages must be resisted.

Varnished pressboard has about one-half the dielectric strength, the insulating power being almost entirely in the varnish film. For this reason the thicker material is not greatly superior to the thin, particularly as the latter is harder, more dense and more highly finished.

Pressboard is made from cotton rags and paper clippings in several grades, and has a thoroughly laminated structure, each 0.003 in. (0.076 mm.) in finished thickness representing a separate layer of pulp, hence impurities are not especially objectionable as they are confined to separate layers.

The principal defects arise from folds in the materials, which have been crushed by the calender rolls during the course of manufacture, thus destroying the mechanical and electrical strength of the finished pressboard.

Special Compounds. For best results, it is essential that electrical coils be thoroughly impregnated with solid insulating compounds.

For use in air, compounds composed of rosins, asphalt, etc., are suitable, but for oil-filled apparatus a material insoluble in the hot oil is necessary.

These compounds must be forced into the coils under heat and pressure, and obviously may melt and run out afterward if apparatus is operated at very high temperatures.

It is believed that the limit in the possibilities of vegetable gum compounds has about been reached, and that for future progress the synthetic gums or artificial rosins offer the best opportunities for improvement.

These compounds, being liquid in the original state, may be forced into the coils while cold. On baking the liquid becomes perfectly hard and solid, and is then insoluble in oil and cannot be remelted.

Variation of Dielectric Strength with Thickness. Why is not the dielectric strength of insulating materials proportional to thickness? The uniform experience with test pieces an inch (25.4 mm.) or less in thickness, shows that the puncture voltage varies between the first power and square root of thickness, and all attempts to prove otherwise, or to develop a universal formula have apparently failed.

Possibly variations in form of the electrostatic field, using identical electrodes, with varying separation to accommodate the different thicknesses, has something to do with it, but can hardly account for the great variations from a straight line law. The fact remains, however, and it is unsafe to calculate the dielectric strength for a given thickness, from tests on a different thickness. Hence, no reliance can be placed on results given per centimeter, or per inch and based on tests of, say one mm. thickness.

Effect of Lamination. The best insulators have usually a finely laminated structure. This is shown in mica, pressboard, and all built-up insulations of cloth, tape, paper, etc.

The value of lamination may be explained in part as follows:

1. Weak spots are confined to one layer and are unlikely to line up throughout.
2. Material being discontinuous, there is less danger that a rupture in one portion will extend to another.
3. If used under oil, the interstices may be filled, thus adding to the strength and excluding air.
4. Thin materials are in general superior to thick in both mechanical and dielectric strength.

Mechanism of Rupture of Dielectrics under High Potential Stress. The exact action taking place during rupture is but imperfectly understood and there seems to be a tendency to lay too much stress on single aspects of the phenomena.

In the most general case it is probable that the following takes place:

1. A molecular strain in the dielectric corresponding to the "displacement", or condenser current.
2. Consequent heating by dielectric hysteresis.
3. Conduction by means of conducting impurities.
4. Conduction by ionization.

The prominence of each of the above will vary with the character of the dielectric, although in the majority of cases it would seem probable that all take place to some extent. Thus, provisionally, the action in each of the chief classes of insulators may be conceived as follows:

Gases—molecular strain and ionization.

Liquids—molecular strain; impurities; ionization.

Solids—molecular strain; hysteresis; impurities; ionization.

In solids, hysteresis is of great effect, and rupture may be almost entirely due to charring from the heat generated by the alternating stress. The dielectric strength of many of the best insulators is reduced 50 per cent by an increase in temperature from 25 to 100 deg. cent.

Arcing Voltage: Surface Creeping. Strictly speaking there is no such thing as the "creeping voltage" of an insulator, the voltage required to arc over a clean insulating surface being nearly independent of the kind of material and character of surface, but determined by the form and arrangement of electrodes and insulation.

It depends indirectly on the capacity of the apparatus considered as a condenser, and the character of the dielectric (as air or oil) which is ruptured by the arc, every " creeping " test being also a puncture test, as is obvious.

Place two electrodes on a sheet of insulating material such as 3/32 in. (2.38 mm.) oiled pressboard about 3 inches (76.2 mm.) apart and apply voltage. If in air the arc will form at or near the surface of pressboard at about 50,000 volts. Now place terminals opposite each other on opposite sides of pressboard and 6 in. (152.4 mm.) from edge. Arc-over will occur at about 40,000 volts. Thus the " creeping " or " arcing " voltage of oiled pressboard is 50,000 volts for 3 in. (76.2 mm.), or 40,000 volts for 12 in. (304.8 mm.) as the case may be.

If two layers of pressboard are used, the arcing distance for the same voltage will be the same in the first case, but greatly reduced in the second, the *capacity* being reduced one half. Thus in designing insulations, such as separating flanges, the arc-over voltage may be increased more readily by making the flange thicker than by increasing the width.

This principle is simple and may often be applied to great advantage.

SUMMARY

1. The principal high-tension tests of insulating materials are stated, and the requirements in testing apparatus defined.
2. Suitable generators, transformers and controlling and measuring apparatus are described and illustrated.
3. The spark-gap for measuring voltage is discussed and the voltmeter coil in transformer recommended.
4. Suitable methods of test are described. The adoption of standard methods and devices is recommended.
5. Spark-gaps for oil testing are discussed.
6. Some characteristics of insulating materials are discussed.
7. Results of actual tests are given in the form of curves.

I desire to acknowledge the great assistance rendered in the experimental work and preparation of this paper by Messrs. M. E. Tressler, M. G. Newman and C. R. Blanchard.

CONCLUSIONS

This paper chiefly represents the author's personal experience and opinions and is intended to be mainly suggestive, and to excite interest in the general subject of high tension insulation and methods of testing, rather than to offer definite solutions of the problems presented.

Results of Tests. The following curve sheets represent some results of tests made by the methods and apparatus herein described and recommended.

Great accuracy in this work is at present unattainable, nor is it claimed for the results given. Some of the curves were made especially for this paper and represent but a single series of observations, while others were made some time ago and have since been confirmed and modified by many additional tests. The latter are ideal curves and do not represent any one series of tests but are believed to be reliable.

The figures given for accuracy represent the probable variations of single points in a series of tests. They apply particularly to the middle of curves, the accuracy being less for lower voltages and greater for higher.

The values of specific capacity given represent the average of a number of measurements on different samples. Individual variations are about 20 per cent plus or minus.

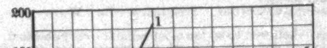

FIG. 20

DIELECTRIC STRENGTH OF OIL WITH VARIOUS SHAPES OF ELECTRODES

Curves.—For 4-in. disks—2-in. balls—1-in. blunt conical points—needle points—4-in. disk and needle point.

Material.—Heavy transformer oil.

Dimensions.—Specific gravity 0.868—viscosity 100 Saybolt at 40 deg. cent.

Composition.—From Pennsylvania crude.

Treatment.—Filtered through dried blotting paper.

Method of test.—Beginning at lowest voltage, each curve is taken up to highest voltage and down again—about 10 to 15 points being taken on each curve. Standard test on oil at beginning and end shows that quality remained nearly constant.

Temperature.—20 to 25 deg. cent. Time—instantaneous. Frequency—60. Wave—sine.

No. of trials.—Each point, about five.

Accuracy of curve.—Plus or minus 10 per cent.

Characteristics.—Puncture voltage depends very largely on shape of electrodes. Curve 1—using 4-in. disks. Curve 2—using 2-in. balls. Curve 3—using 1-in. blunt conical points. Curve 4—using needles. Curve 5—using 4-in. disks and needle.

Specific capacity.—2.5 from 25 to 100 deg. cent.

Notes.—These are standard curves, suitable for use in design. They are based on the same data as those given in the paper on "The Dielectric Strength of Oil" (TRANS. A.I.E.E., 1909) by H. W. Tobey.

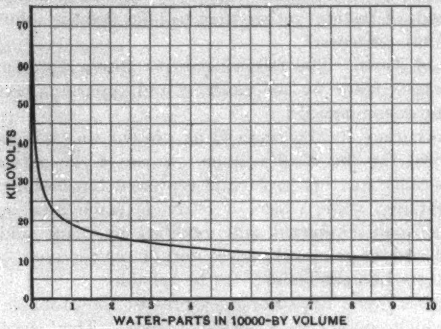

FIG. 21

WATER IN TRANSFORMER OIL

Curves.—Dielectric strength versus content water.
Material.—Heavy transformer oil.
Dimensions.—Specific gravity, 0.87—viscosity at 40 deg. cent. = 100 Saybolt.
Composition.—From Pennsylvania crude.
Treatment.—Oil is first filtered through dry blotting paper, and oil and water then emulsified by mechanical shaker.
Method of test.—Standard spark gap 0.2 in. between 0.5-in. disks—two separate emulsions—four samples of each—five trials on each sample.
Temperature.—20 to 25 deg. cent. Time—instantaneous. Frequency—75. Wave—sine
No. of trials.—each point, 40.
Accuracy of curve.—plus or minus 5 per cent—believed to be the most reliable ever published
Characteristics.—Extremely rapid reduction of dielectric strength by minute quantities of water—under 0.01% if thoroughly mixed.
Specific capacity.—dry oil = 2.5 at 25 to 100 deg. cent.
Notes.—Practically identical results obtained on light oil—specific gravity 0.85—viscosity at 40 deg. cent. = 40 Saybolt.

Equation of curve.—$y = \dfrac{19.2}{x^{.264}}$

OILED PRESSBOARD

Curves.—Dielectric strength versus thickness of sheet.
Dimensions.—0.011 in. to 0.122 in. thick.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square edge flat disks 4 in. in diameter under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one to four.
Accuracy of curve.—10 per cent plus or minus. Curve is based on but a few trials, hence is not very reilable, but shows typical results.
Characteristics.—Material is variable; results depend largely on time of application of stress.
Specific capacity.—4.9 at 20 to 25 deg. cent. under oil.

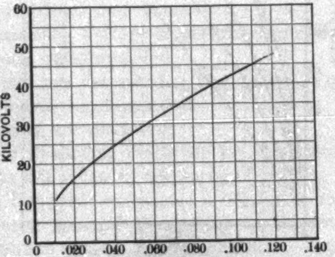

FIG. 22

Notes.—Total time of test is about five minutes (average) giving rather low results.

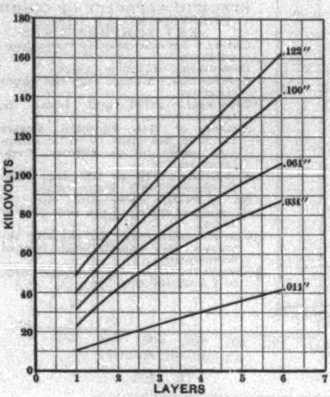

FIG. 23

OILED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thicknesses of board.
Dimensions.—0.11 in. to 0.122 in. thick—one to six layers.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square edge flat disks 4 in. in diameter under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one to four.
Accuracy of curve.—10 per cent plus or minus. Curve is based on but a few trials, hence is not very reliable, but shows typical results.
Characteristics.—Material is variable; results depend largely on time of application of stress.
Specific capacity.—4.9 at 20 to 25 deg. cent. under oil.
Notes.—Total time of test is about 5 minutes (average) giving rather low results.

VARNISHED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thicknesses of board.
Dimensions.—0.035 in., 0.067 in. and 0.097 in. thick—one to six layers.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and given two coats of varnish.
Method of test.—Between square edge flat disks 4 in. in diameter under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave-sine.
No. of trials.—Each point, one to four.
Accuracy of curve.—10 per cent plus or minus. Curve is based on but a few trials hence is not very reliable but shows typical results.
Characteristics.—Dielectric strength low but fairly uniform, depending largely on varnish film; nearly proportional to total thickness within limits of tests.

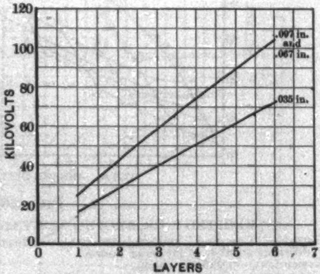

FIG. 24

Specific capacity.—2.9 at 20 to 25° C. on 0.097-in. board.
Notes.—Same results were obtained on 0.067-in. and 0.097-in. board. Thin board is superior to thick in hardness, density and finish, thus compensating for difference in thickness. Thickness given is as actually measured after varnishing.

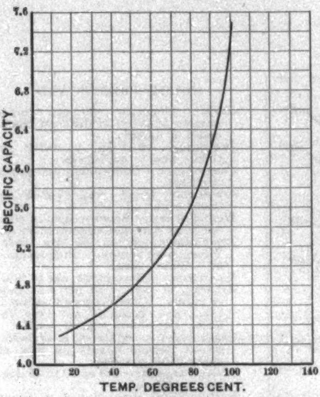

FIG. 25

SPECIFIC CAPACITY OF OILED PRESSBOARD AT DIFFERENT TEMPERATURES

Curves.—Specific capacity versus temperature.

Dimensions.—0.125 in. thick.

Composition.—Cotton rags and paper clippings.

Treatment.—Dried and boiled in transformer oil.

Method of test.—Between square cornered flat disks 10 in. in diameter under oil at different temperatures.

Temperature.—13 to 100 deg. cent. Frequency—60. Wave—sine.

No. of trials.—Each point, one.

Accuracy of curve.—5 per cent plus or minus.

Characteristics.—Specific capacity increases very rapidly with rise of temperature.

Specific capacity.—4.3 at 13 deg. cent. to 7.5 at 100 deg. cent.

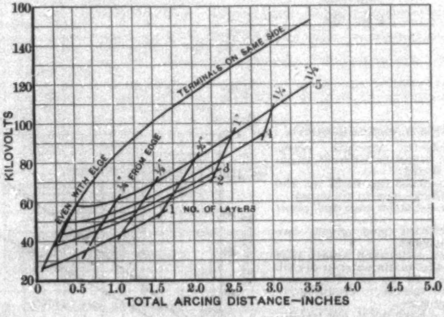

FIG. 26

"CREEPING" OR ARCING VOLTAGE ON OILED PRESSBOARD

Curves.—"Creeping" voltage between electrodes on same or opposite sides of board—using different number of layers of board.

Dimensions.—0.095 in. thick.

Composition.—Cotton rags and paper clippings.

Treatment.—Dried and boiled in transformer oil.

Method of test.—Between round flat electrodes 4 in. in diameter or resting on flat semicircular electrodes of 2-in. radius the rounded faces of electrodes facing each other on same side of board. All electrodes have square corners where in contact with board. Tests under oil.

Temperature.—20 to 25 deg. cent. Time—instantaneous. Frequency—60. Wave—sine.

No. of trials.—Each point, five to ten.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Curves show the great difference in arcing voltage for a given distance, depending on whether terminals are on same or opposite sides of board.

Condenser capacity.—Practically zero with terminals on same side of board and very large when on opposite sides.

Notes.—This shows that the "creeping" voltage is not a constant of the material but depends on the arrangement of parts.

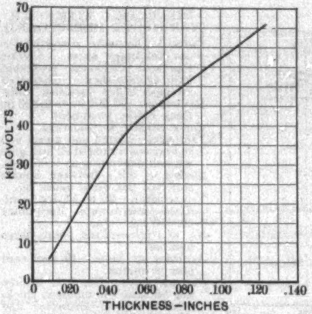

FIG. 27

DIELECTRIC STRENGTH OF OILED PRESSBOARD

Curves.—Dielectric strength versus thickness of sheet.

Dimensions.—0.007 in. to 0.125 in. thick.

Composition.—Cotton rags.

Treatment.—Dried and boiled in transformer oil.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, large number.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Extremely high dielectric strength.

Specific capacity.—4.3 at 20 to 25 deg. cent. under oil.

Notes.—This is a standard curve based on many tests.

DIELECTRIC STRENGTH OF OILED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thickness.

Dimensions.—One to six layers of sheets, 0.031 in. to 0.125 in. thick.

Composition.—Cotton rags.

Treatment.—Dried and boiled in transformer oil.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, small number.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Dielectric strength of 0.031-in. is proportional to total thickness but of thicker sheets increases at slower rate.

Specific capacity.—4.3 at 20 to 25 deg. cent. under oil.

Notes.—This is a standard curve based on long experience.

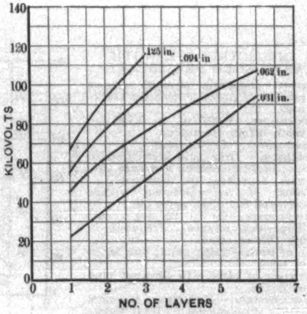

FIG. 28

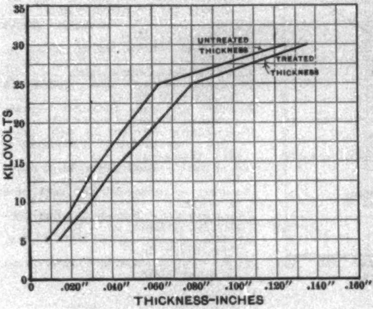

FIG. 29

DIELECTRIC STRENGTH VARNISHED PRESSBOARD

Curves.—Dielectric strength versus thickness sheet. Curves represent thickness varnished and unvarnished. Dielectric strength is for varnished only

Dimensions.—0.007 in. to 0.125 in. thick before treatment.

Composition.—Cotton rags.

Treatment.—Dried and given two to four coats linseed oil and gum varnish depending on thickness.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, large number.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Curve is broken line because the different thicknesses vary in character and treatment. Number of coats of varnish increases with thickness.

Notes.—This is a standard curve based on long experience.

DIELECTRIC STRENGTH VARNISHED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thickness.

Dimensions.—0.007 in. to 0.125 in. thick before treatment.

Composition.—Cotton rags.

Treatment.—Dried and given two to four coats linseed oil and gum varnish, depending on thickness.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, one series of tests.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Dielectric strength nearly proportional to total thickness.

Notes.—This is a standard curve.

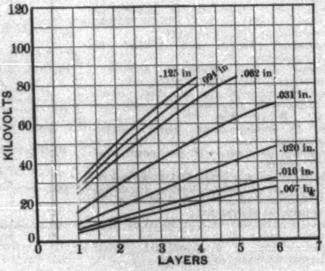

FIG. 30

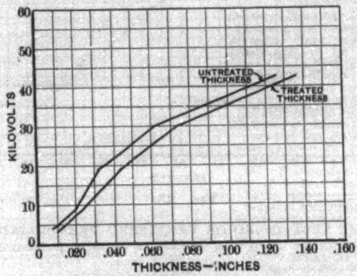

FIG. 31

DIELECTRIC STRENGTH OILED PRESSBOARD

Curves.—Dielectric strength versus thickness sheet; curves represent thickness treated and untreated; dielectric strength is for treated only.
Dimensions.—0.007 in. to 0.125 in. thick, before treatment.
Composition.—Cotton rags.
Treatment.—Dried; boiled in linseed oil; the 0.031-in. to 0.125-in. board also received two coats varnish.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one series of tests.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Curve is broken line because the different thicknesses vary in character and treatment.
Notes.—This is a standard curve based on long experience.

DIELECTRIC STRENGTH OILED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thickness.
Dimensions.—0.007 in. to 0.125 in. thick before treatment.
Composition.—Cotton rags.
Treatment.—Dried; boiled in linseed oil; the 0.031-in. to 0.125-in. board also received two coats varnish.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one series of tests.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Dielectric strength nearly proportional to total thickness.
Notes.—This is a standard curve.

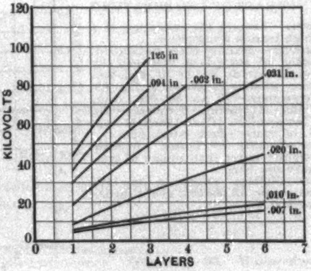

FIG. 32

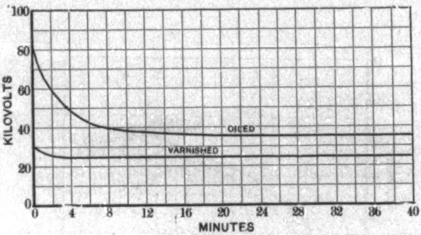

FIG. 33

TIME TEST; OILED OR VARNISHED PRESSBOARD

Curves.—Dielectric strength versus time for oiled or varnished pressboard.
Dimensions.—0.94 in. thick.
Composition.—New cotton rags.
Treatment.—Oiled pressboard, dried and boiled in transformer oil; varnished pressboard, dried and treated with four coats varnish.
Method of test.—Between flat, square cornered disks, under oil. A definite voltage applied and held till puncture occurs. Spark gap contains about 15 gals. of oil, hence heating is slight.
Temperature.—20 to 25 deg. cent. Time—until rupture. Frequency—60. Wave—sine.
No. of trials.—Oiled board, average of two curves, 10 points each.
Accuracy of curve.—Plus or minus 10 per cent on oiled pressboard; plus or minus 20 per cent on varnished pressboard.
Characteristics.—Oiled board gives definite results on a smooth curve; varnished board gives very irregular results; curve shows general tendency only.
Specific capacity.—Oiled board =4.3 under oil at 20 to 25 deg. cent.
Notes.—As opportunity for cooling was excellent, the heating effect must have been very small. Results under heat may be expected to be very different.

INCREASE OF ENERGY LOSS IN INSULATION WITH INCREASE OF TEMPERATURE

Curves.—Loss in the insulation of a high tension transformer.
Material.—Mainly oiled pressboard.
Method of test.—Loss measured by wattmeter at middle of high-tension winding as shown in Fig. 13.
Temperature.—23 to 58 deg. cent. Time—11½ hours. Frequency—60. Temperature of oil taken at top.
No. of trials.—Each point, one.
Characteristics — Losses increase slightly faster than square of temperature rise.
Note.—Voltage wave has an 11th harmonic, 12 per cent of the fundamental.

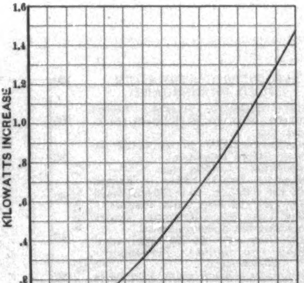

FIG. 34

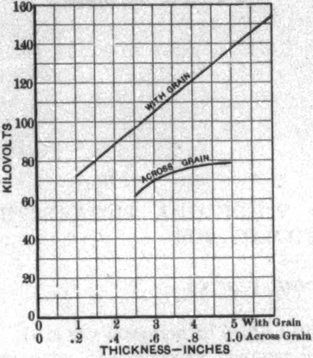

FIG. 35

DIELECTRIC STRENGTH OILED WOOD

Curves.—Dielectric strength with and across grain, versus thickness wood.

Material—Hard maple.

Dimensions.—⅛ in. to 1 in. across grain; 1 in. to 6 in. with grain.

Treatment.—Across grain, boiled in transformer oil under vacuum; with grain, dried under vacuum, boiled at atmospheric temperature.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, one to three; three points across grain; 5 points with grain.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Dielectric strength across grain increases much slower than thickness but with the grain is proportional to thickness.

Specific capacity.—Across grain = 4.1 at 20 to 25 deg. cent. under oil.

Notes.—Test with and across grain on samples treated by different methods a long time apart. Wood seems to be identical in quality however

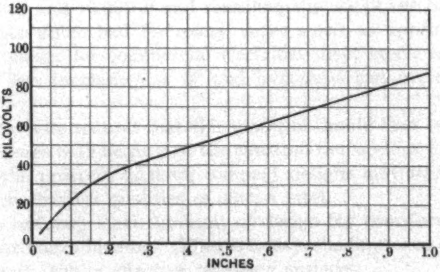

FIG. 36

DIELECTRIC STRENGTH OF HARD FIBER

Curves.—Measured on single thicknesses.

Dimensions.—0.031-in. to 1-in. sheets.

Composition.—Chemical hard fiber.

Treatment.—Dried before testing.

Method of test.—Between flat, square cornered disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

Accuracy of curve.—About 10 per cent plus or minus.

Characteristics.—Results depend largely on dryness of fiber.

Notes.—Results on fiber of different colors seem to be identical.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers February 14, 1911.

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HYSTERESIS AND EDDY CURRENT EXPONENTS FOR SILICON STEEL

BY W. J. WOOLDRIDGE

It is my intention to bring before the Institute as briefly as may be, the apparent changes in general direction of curves required for predetermining core losses of apparatus, especially transformers, in which silicon steel is used.

When this alloyed steel first came into use, some years ago, curves were drawn up based on losses found in samples tested at 5,000 B and 10,000 B and retaining the use of the Steinmetz exponents which had for many years stood as approximately correct values for commercial electrical sheet steel, *viz.*, eddy current loss increasing as B^2 and hysteresis loss increasing as $B^{1.6}$.

It was quite natural that this material should first be used in transformers both because of the constant demand for lower core losses, the prospect of more compact designs and also because of the mechanical qualities of silicon steel.

With ordinary steel the limit of design for transformers was along the line of heating. That is to say, the limit was the watts per square inch of effective radiating surface.

With the lower watts per pound of the new steel an increase in core density above that generally used in the old material seemed allowable and was also desirable in order to offset the higher cost per pound of the steel. Core loss curves made on such transformers showed the material at low densities to be in accord with design curves, but at medium densities (12,000 B for instance) the loss was considerably above anticipated results.

In seeking the cause of the trouble the well established exponents which had proven satisfactory for so long, were not at first considered. The test curves when carried further, to relatively high densities, showed a continued increase but not logarithmic. It was noted in such cases that the power factor decreased rapidly, this decrease coinciding in a marked degree to the increased core loss as shown by the wattmeters. The higher loss was, therefore, assumed to be due at least in part to incorrect wattmeter readings and in part to a possible change in wave form.

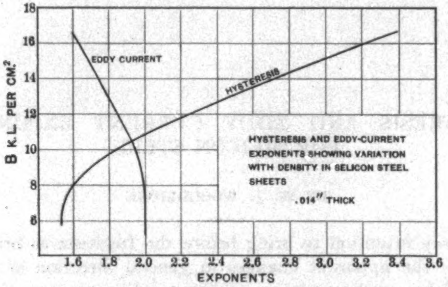

FIG. 1

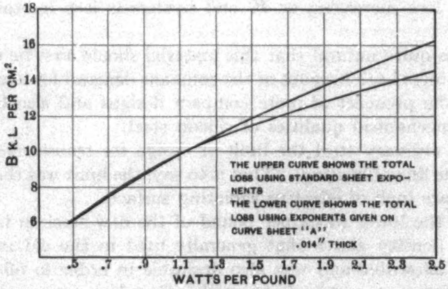

FIG. 2

Later, the development of the iron clad instrument, giving correct readings at low power factors, showed that the premise regarding the effect of incorrect wattmeter readings to be largely a wrong one. Tests on a small core carefully tested on sine wave and then used in conjunction with the transformer under test, enabling a ready and convenient correction for wave form, gave further evidence that the high core loss at high densities was inherent.

Careful tests on variously proportioned cores, such as rings without gaps, rectangular cores, and complete transformers, were found to agree closely and finally led to the inevitable conclusion that the exponents regularly used for ordinary steel did not hold for silicon steel.

This has been confirmed by several other investigators and has been published in the Bulletin of the Bureau of Standards, and to some extent by the German technical press.

Both hysteresis and eddy current exponents were determined and it was found these were not a constant value for either component, the hysteresis increasing more and more rapidly as the density increased, while the eddy current decreased but to a lesser extent. The average values found are shown in the curves Fig. 1. In transformers, the decreasing eddy current loss does not materially offset the increasing hysteresis from the fact that the eddy current loss in thin sheets is such a small proportion of the total.

Fig. 2 is given to show the relation between two curves, the upper one of which is plotted using the old ordinary steel exponents and the lower curve being plotted using the exponents shown in Fig. 1, assuming the same values at 10,000 *B*.

The values are based on tests made on 0.014-in. sheet steel obtained from several steel makers in this country and abroad.

It is interesting to note that the hysteresis exponent in the neighborhood of 16,000 *B* is more than double the old value as used for ordinary steel.

A paper presented at the Pittsfield-Schenectady mid-winter convention of the American Institute of Electrical Engineers, February 14, 1911.

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COMMERCIAL PROBLEMS OF TRANSFORMER DESIGN

BY H. R. WILSON

One of the most important problems confronting a designing engineer is the compromise between the design which, in his opinion, is best but too expensive for competition, and the design which can be built to barely meet guarantees and which can be sold for the lowest possible price. The designing engineer is at times compelled to cater to the idiosyncrasies of certain customers, whose special requirements, experience has proved, are unnecessary and detrimental to good construction, but which will be furnished by competitors who are less conscientious in this respect.

It is doubtful whether any line of apparatus is subject to such wide variation in requirements as transformers. Capacity, voltage (both primary and secondary), taps, heating, overloads, efficiency, regulation and overall dimensions must all be taken into consideration, and the best balance obtained, so that the design will conform to the requirements of the majority of customers.

For a line of transformers varying in capacity from 100 kw. to 4000 or 5000 kw., and in voltage from 2200 volts to 110,000 volts, the best solution of the above problems is not an easy one.

If it were possible to treat each transformer as an individual unit, the difficult problem of standardization would be eliminated, but for extensive production, this is not permissible. The standardization of parts for a line of transformers covering a wide range in capacity and voltage, demands a large number of special tools, patterns, dies, etc., the cost of which is a big item, and in order to keep down this initial cost, the number of patterns, dies and tools must be reduced to the minimum, consistent with economical production. On the other hand, standardization has an important bearing on delivery; the greater the number of different parts which can be carried in stock, the shorter will be the time necessary for the production of the apparatus.

The principal transformer parts which may be standardized are: the case, punchings and size of copper strip.

Should a line of round tanks running from 3 ft. (0.91 m.) to 8 ft. (2.4 m.) diameter, vary in steps of 2 in. (5 cm.) or should the gradient be 2 ft. (61 cm.)? The former figure is obviously too small and the latter too large, but where should the line be drawn? If a line of dies for punching laminations is to be established, what will be the minimum number that can be used without sacrificing too much of the wire space on intermediate sizes? The carrying of a large stock of drawn copper necessitates the investment of much capital and consequently considerable importance should be attached to the selection of strips, in order to avoid carrying in stock, a large number of sizes for which there is very little call and which may be on hand for several years. On the other hand, too small a number of strips may mean, in many cases, the use of a larger size strip than would answer the purpose.

Another question which has been frequently discussed, is the maximum economical capacity gradient for small transformers which are to be carried in stock. Shall the standard sizes under 5 kw. be 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 kw. or will half of this number serve the purpose?

The importance attached to operating data is sometimes a handicap in a good design. Consider the question of efficiencies in its components of core loss and copper loss. Assuming a predetermined number of turns of required cross-section, the size of the wire space or window depends upon the amount of insulation used, and the relatively small amount of space required for the copper compared with that taken up by the insulation (especially in high voltage units), is apt to be surprising. The latter frequently requires from three to fifteen times as much room as the former. It will therefore readily be seen that a reduction in the insulation factor of safety, will give a reduction in core loss and that a low core loss obtained in this manner may easily deceive a prospective customer who cannot be expected to be acquainted in detail with the strength of the various insulating materials and methods of using the same.

The relation of efficiency and cost must also receive due consideration, and a choice between the least expensive, low efficiency design and the more costly high efficiency design must be made. The low cost of power development calls for the former and the latter is more advantageous where the saving resultant from a reduction in losses overcomes the interest on the first cost of installation.

A much discussed subject has been the relative proportion of overall height to floor space, especially for transformers of 500 kw. and above. A certain station layout has plenty of available floor space, but demands a transformer of limited height, while, on the other hand, another station is crowded for floor space but has head room more than necessary. For a station situated in large cities where land is valuable, the unit with small floor space seems to be better suited, while a station located in less valuable territory allows the reverse conditions. These local conditions must all be considered when laying out a line of parts which will be best adaptable for fulfilling the various requirements.

Let us consider, however, a situation where neither overall dimension is limited. What relation of height to floor space for a round or square case, will be most suitable for the average station? Shall the proportion of height over cap to floor space be 1.5: 1, or 2.5: 1, *i.e.*, will over all dimensions of say 5 ft. (1.5 m.) diameter by 7.5 ft. (2.2 m.) high be better than 4 ft. (1.2 m.) diameter by 10 ft. (3 m.) high? It would be very interesting to know if the majority of customers have a preference for small floor space and considerable height, or greater floor space and less height.

A finished outside appearance is desirable in all apparatus, but the influence of such appearance in selling a transformer is a debatable question. Is it desirable to expend the additional money necessary to obtain this finished article, or will less paint and a rough surface be fully as acceptable? Shall the same care be given to the internal parts or will rougher work pass unnoticed? If transportation facilities allow the shipment of a transformer assembled in the case, the unit is very apt to be placed in service without investigation of the inside construction, and consequently the extra care and finish pass unnoticed, at least until revealed by a general investigation.

Until the past few years power transformers were designed with a comparatively low reactance, about 2 per cent or 3 per cent, and, as the $I R$ drop per cent decreases as the capacity increases, better regulation was obtained on the larger size units. Later experience has proven that the higher the reactance, the greater is the ability of the transformer to withstanding short circuits. It is therefore desirable to have high reactance in transformers of large capacity; especially where the total power behind the transformer is many times the capacity of the transformer bank. The result of increasing the reactance as the capacity increases, is that the regulation on loads of low power factor is considerably poorer for the larger size units than it is for those of smaller capacity. This is not however objectionable, because on large power transformers there is usually no need for good regulation.

As the modern grades of steel are practically non-aging, the tendency has been to run up the density, thereby obtaining a considerable reduction in both the amount of iron and copper; the size of the core decreasing in proportion to the increase in density and the weight of copper in proportion to the reduction in the mean length of turn. If the cost of the copper and iron is about equally divided, and a decrease of 10 per cent in density gives an increase of 10 per cent in the amount of steel, and about 4 per cent in the amount of copper, the total increase will be 7 per cent.

The principal disadvantage of a high density is the large increase in magnetizing current and core loss when operating under over-voltage conditions, *i.e.*, with a density of 50,000 lines per sq. in. (8000 per sq. cm.) for normal voltage, the per cent increase in magnetizing current and core loss when operating at 10 per cent over-voltage, is not nearly as great as will be the case when the density at normal voltage is 80,000 to 90,000 lines per sq. in. (12,400 to 15,500 per sq. cm.). The purchaser, who is apt to operate his lines above the normal rated voltage will do well to consider this question when ordering transformers.

The manner in which transformers are rated and guarantees made when operation is to be at power-factor loads, may be misleading to a customer who is not familiar with transformer design. A transformer may be required to deliver a specified number of kilowatts at a low power-factor, but through a misunderstanding between the manufacturer and the purchaser, a unit of the same numerical capacity rated on a kilovolt-ampere basis may be furnished instead of one rated on a kilowatt basis at the power-factor on which it is to operate. Now that the practice of rating transformers on a kilovolt ampere basis has been standardized, misunderstandings of the above sort should be eliminated.

The A. I. E. E. rules state that the temperature rise of a transformer should be based on the temperature of the surrounding air. The cooling medium for oil-insulated self-cooled and for air-blast transformers is the surrounding air, but for oil insulated, water-cooled units the cooling medium is water, and it is only logical to consider the temperature rise above that of the ingoing water and illogical to refer to the temperature of the room. The purchaser of this type of transformer who specifies that the temperature rise shall be based on the temperature of the surrounding air is very apt to receive a unit having 10 deg. cent. higher heating than if he had stated that the temperature rise should be above the ingoing water, *i.e.*, for example, a guarantee to the effect that the temperature rise shall not exceed 40 deg. cent. above the temperature of the surrounding air at 25 deg. cent. with the ingoing water at 15 deg. cent. is in reality a unit having a temperature rise of 50 deg. above the water at 15 deg. cent., and consequently is a 10 deg. cent. hotter transformer than if the guarantee was 40 deg. cent. above the cooling medium, which is the water at 15 deg. cent.

The engineering and commercial conditions are so vitally related, that all phases of the situation must be considered from both points of view, and therefore the best general design of a line of transformers is the one which contains no features which are commercially detrimental, and yet will satisfactorily fulfill the requirements which will be demanded in actual service.

DISCUSSION ON "HIGH-TENSION TESTING OF INSULATING MATERIALS," "HYSTERESIS AND EDDY CURRENT EXPONENTS FOR SILICON STEEL," "COMMERCIAL PROBLEMS OF TRANSFORMER DESIGN," SCHENECTADY, FEBRUARY 14, 1911.

C. P. Steinmetz: Mr. Hendricks' paper on "High Tension Testing of Insulating Materials" is not simply a paper, but rather a compendium of our knowledge of the characteristics of insulating materials, the methods of testing, the difficulties met, and the errors to be guarded against, and how these errors may be avoided and reliable results secured.

With the rapid development of the electrical industry in the last ten years we have advanced to higher and higher voltages, and thereby the characteristics of the insulating materials have become of increasing importance, so that probably the insulations of our electrical apparatus constitute the most important materials which enter into the construction. This has been recognized by the Institute, more particularly by its Standardization Committee, and if we compare the first report of 1897, in which we find only a short paragraph dealing with high voltage tests, with a later report, that of 1907, we find in the latter quite an explicit discussion on the methods of testing, the different precautions and safeguards to be employed, on the use of the voltmeter and the use of the spark gap, etc. Nevertheless, even the 1907 report is already somewhat antiquated, and at least those engineers who have to deal with high voltage measurements, feel that the specifications of the Institute might be revised, and therefore a motion may be advisable to refer this paper to the Board of Directors for recommendation to the Standardizing Committee in studying and further investigating the methods of high voltage testing.

There are a number of important questions raised in this paper, and among them is the question of the spark gap. Theoretically the spark gap is the ideal and only correct method of measuring disruptive strength, as it measures the strain on the apparatus tested, by comparison with the strain on the standard material, the air, under standard conditions of experiment, the spark gap between needles under specified conditions. The great difficulty is in securing standard conditions, and herein lies most of the difficulty met in the spark gap method. When this method was standardized, we had no knowledge of the effect of transient voltages, on the difference in action of one dielectric and another dielectric, with different times of the application of voltage, which means that one spark gap may be equivalent to a testing material for one amount of energy, and a different spark gap for a larger or a lesser amount of energy, so that the entire field of transient voltages enters as a fundamental factor and indeed, as the most disturbing cause in the use of the spark gap. Nevertheless, theoretically the spark gap is the most correct method, and it therefore requires further investigation, to see how we can guard against possible errors.

The voltmeter, after all, does not measure the disruptive strain, but it measures the effective value of the voltage, from which we can calculate the maximum value, and thereby the dielectric strain. This calculation is based on a knowledge of the wave shape of the voltage. It requires a sine wave generator. Practically all modern alternating current generators give electromotive force waves which are so nearly sine waves that the error in a high voltage test made by the use of such a voltage wave on the test piece, would be negligible. But it is not the shape of the voltage wave at the generator which is the source of trouble, but the great difficulty is to get the same wave at the testing piece. There intervenes the step-up transformer, carrying a great leading current full of higher harmonics, the transient effects of its capacity, etc., and herein lies the great difficulty with the voltmeter measurements, but as the author has shown in the paper, by using the voltmeter as close as possible to the test piece, this difficulty can be largely overcome.

There still remains the effect of transient phenomena, and one of the important results of this paper is, that the spark gap which measures the maximum voltage does not eliminate the danger of the error caused by transient or momentary voltage peaks, because there enters the time element, which is different with different shapes of spark gaps; is different with liquids, such as oils, and different again with solid insulating materials. From the investigations of the last years, this entire field seems to be thrown open again for further consideration, and in the recognition of this lies one of the most important features of this paper.

With the rapid increase of operating voltages, and the increasing demands for reliability of operation, the study of insulating materials has enormously increased in importance.

Henry Pikler: The papers of this afternoon deal with subjects which are interesting chiefly to the manufacturing and designing engineer. The few remarks I intend to make in connection with these papers are from such an engineer.

The subject of the first two papers, one by A. B. Hendricks, Jr., and the other by W. J. Wooldridge, is properties of material. This truly belongs in the realm of physics and should be treated by the physicist. The physical methods of investigating the properties of material are more refined and exact than the methods at the disposal of the commercial manufacturing engineer. I look at the papers presented in this light. In spite of the comparatively crude means at the disposal of the manufacturing engineer, the paper presented by Mr. Hendricks is a very valuable one not so much for the numerical data it discloses, but chiefly for the reason that it shows the means and ways which the manufacturing engineer should adopt and pursue for the purpose of obtaining reliable results.

To discuss the paper in detail, tests are given on liquids and solids. The materials entering into the construction of electrical apparatus of to-day consist of iron, copper and insulating materials. While copper and iron are not subject to deterioration under normal conditions, the insulating material deteriorates rapidly in comparison. A superficial reader of this paper is apt to get the impression that fibrous insulating materials are very important and of great value, because the paper deals with them at great length. As to the value of fibrous materials, I wish to state that I consider it unwise to rely on them entirely. The fibrous insulating material should be considered as a binder only. It is the oils and the varnishes which make the fibres really do the work. The less we rely on an insulating material of this type for the purpose of insulation, and the more on the mechanical disposition of the various parts to be insulated, the more durable will be the apparatus manufactured.

The old methods and principles of insulation I beg to be allowed to term " the ostrich policy ". The tendency was to *hide* the various parts to be insulated from each other and to wrap them up in a large mass of fibrous material like tape, paper, etc. My ideas of insulating modern electrical apparatus are as follows:

1. The proper mechanical disposition of the various parts which are to be insulated from one another. Smooth surfaces should be exposed between parts. Sharp corners and small radii should be avoided.

2. Small and uniform electrostatic capacities are to be sought for the parts to be insulated from each other.

The adoption of the first principle will result in a uniform and a low dielectric flux density between parts and every cubic inch of the insulating material between these parts will be under uniform stress, and therefore may be used most efficiently.

The adoption of the second principle will prevent the building up of a very high potential difference, between parts to be insulated which otherwise may act as highly charged condensers.

After the first two requirements have been fulfilled, the insulating proper should consist of the following:

3. The parts to be insulated from one another should be spaced at proper distances so as to present in the way of the discharge paths between the parts, either a wall of insulating material or a creeping surface of proper magnitude.

4. Extract the moisture from all fibrous material. Coat all the surfaces and fill all space with an insulating material of high dielectric strength.

It will be found that by the adoption of these principles in the method of insulating, a great deal of expensive material will be saved, and that the highest class of insulation of *lasting* qualities will be obtained.

I do not agree with Mr. Hendricks in his statement that the auxiliary winding on the testing transformer core should be used in preference to the direct method of measuring the voltage either by a spark gap, or by other means. I consider his suggestion a fundamental error: What we want to know is the actual potential difference between parts of the apparatus under test. When we measure the voltage on the auxiliary coil of the test transformer, what are we doing? We measure the induced e.m.f. Now we know that the terminal voltage is quite different from the induced electromotive force for several reasons—As for instance, the electrostatic capacity of the testing transformer itself, the electrostatic capacity of the piece under test. All of this cannot be neglected even if the testing transformer has a very good regulation, but supposing the testing transformer *has* a very good regulation, then we might just as well go by the ratio and not use an auxiliary coil on the testing transformer at all.

I do not agree with Mr. Hendricks that a shell type transformer is better suited for the purposes of a high voltage testing transformer than a core type.

His reasons are the larger cross-section of core, and consequently the smaller number of turns in this shell type transformer. I do not see why in a core type transformer a larger section of core could not be used and consequently a smaller number of turns. Moreover, the core type transformer allows the high-tension windings to be distributed over a greater length, and consequently cut down the potential difference, the distances and the electrostatic capacity between parts. It admits of a better regulation. By cross connecting the two halves of the high tension winding, we will obtain an absolutely uniform and comparatively low potential difference between the two halves of the winding on the two legs.

The greatest value of this paper I see is that it will lead to the standardization of the properties of insulating material. This would be very useful, particularly from one point of view, that is, it will create a relation based on something standard between the purchaser and supplier of insulating materials.

As to the second paper by Mr. Wooldridge, on "Hysteresis and Eddy Current Exponents for Silicon Steel", I noted with great interest the results published. I feel, however, that these results should be looked at with a great deal of skepticism, because this paper gives nothing else but the results of experiments. These results are quite different from the data we had on this subject in the past. There are absolutely no details of either of the methods of testing nor of the calculation given. Therefore, this paper does not admit of discussion.

The third paper presented to us is by H. R. Wilson, entitled, "Commercial Problems of Transformer Design".

At the very outset of this paper a principle is enunciated which I consider fundamentally wrong. I cannot accept the statement that "one of the most important problems confronting a manufacturing engineer is the compromise between the design, which in his opinion is best, but too expensive for competition, and the design which can be built to barely meet guarantees, and which can be sold for the lowest possible price." My experience teaches me, and I think that the majority of designers will agree with me, that it is a rule, almost without exception, that the most economical design is that which involves simplicity in construction. The simplest is always the best, and at the same time the cheapest. It does not follow as a necessity that if we put too much material into the apparatus that it will have the highest efficiency or that it will do the best. On the contrary, it will be found in most cases that economy in material will lead to high efficiency if the material is properly used.

I heartily agree with Mr. Wilson that " the designing engineer is at times compelled to cater to the idiosyncrasies of certain customers whose special requirements, experience has proven, are detrimental to good construction, but it will be furnished by competitors who are less conscientious in this respect." To this point I wish to add that keen business competition has led to excesses in this respect. For this reason I feel that the recommendations of the Standardization Committee of the A. I. E. E., with regard to definitions of output and guarantee, overload and heating should be more closely followed.

There is one paragraph in this paper referring to the finish or the outside appearance of apparatus. By all means a neat and good looking finish should be demanded in preference to a rough finish, for the simple reason that neglect of any one detail is apt to introduce neglect of other details, and in general is contrary to good discipline which requires care in every detail.

Ralph D. Mershon: I did not expect to discuss these papers at all, and do not feel qualified to discuss them, because I have not previously read any of them. The one by Mr. Hendricks looks extremely interesting, and I wish he had read it in full so that I might have been better qualified to take part in the discussion.

There is one point Mr. Pikler brought up, in which he took issue with Mr. Hendricks, but in which I do not agree with him. That is the possibility of getting correct voltage readings by means of a voltmeter testing coil. I think the accuracy of the results of such a coil will depend on where the coil is located. For instance, if it were practicable to wind the wire of the test coil beside the wire of the high voltage coil, we should unquestionably get on the voltmeter a measurement to all intents and purposes the voltage at the terminals of the high-tension coil A measurement which when corrected for the ohmic drop in the high tension, would give exactly this voltage. Now it is not practicable to so wind the test coil but it is possible to so locate it as to accomplish practically the same result.

In the high voltage measurements at Telluride 1896, the transformers used were not especially wound with reference to this method of measurement, but I selected one of the coils of the transformer for use as a voltmeter coil and from this coil obtained the voltage readings and also the voltage for the wattmeter. The facilities for checking up the accuracy of this method of voltage measurement at Telluride were not of the best, but we made a great many test readings by attaching the power transformer to the line, putting various amounts of line on so that there were different amounts of leading current, reading the voltage from the test coil of the power transformer, and at the same time reading the line voltage by means of a step down or voltmeter transformer. So far as we could determine the measurement from the test coil was an accurate one. Later, in building the transformers for the high voltage investigation at Niagara, I wanted to have a great deal more elaborate means of insuring accuracy of voltage readings. I wanted to have a number of test coils arranged with elaborate care as to location and construction in the endeavor to approximate the results of a test coil with its wire wound turn for turn alongside that of the high voltage coils. Mr. Moody assisted me in that matter. In fact the final success of the transformers was largely due to the work that he and his assistants did in the design of them. He thoroughly convinced me, by a set of rather elaborate tests, that the method he proposed for using a single test coil instead of a number, was entirely effective. It was, briefly, that of locating the test coil in a position which was a compromise between the location if the test coil were wound directly on the iron and the location if it were wound in the manner first above indicated. The tests for determining the accuracy of the test coil so located were made under various conditions of load and power factor, and I had every reason to believe that the voltage produced by the test coil was, under all conditions, practically proportional to and in phase with the voltage on the high voltage terminals of the power transformer.

William L. Puffer: Mr. Hendricks has presented the results of experiments in the course of which those of us who have attempted anything of the kind realize that he has met and overcome some pretty hard problems. Some of us have been through these troubles and know the difficulties of making high-potential measurements, and I want to go on record as saying that I believe the most accurate method of determining the voltage of such high-tension transformers is by the method of the exploring coil. A good many years ago I used a special method which I devised as a part of a high-voltage testing set at the Massachusetts Institute of Technology and which has not been referred to here this evening. The transformer was wound with the high-voltage coil in sections of approximately ratios of 1-1-2-4, etc. A 2000-volt direct-reading static voltmeter was used and the exact ratios of the various coils measured. During any measurement this method permitted the determination of a fractional part of the high voltage by a method which was affected by all of the possible reactions of the testing current.

The ratio of the voltmeter reading to the maximum was determined by the contact method, the Braun tube and finally, as the instrument was developed, by the oscillograph. The generator used was a Mordey, connected to a set of transformers used as a compensator to supply a suitable voltage for the primary side of the testing set. At that time I made many experiments to see whether the voltmeter method followed the spark gap method, and I am sorry to say that I could never get two curves nearly enough alike to represent good engineering practice.

I regret I have not had time to read the paper of Mr. Hendricks as there are many interesting points I would like to take up, and I thank you for the opportunity of saying these few words.

A. S. McAllister. The author has not defined his two terms, hysteresis and eddy currents. In separating these two he has made certain assumptions, and on the basis of those assumptions has separated the measurable losses into two parts. I wish to mention what seems to me the only source of change in the so-called eddy current and to criticise the method of separation. The eddy currents are produced by voltages, the value of which depends on the flux. Therefore, if the resistance of the path through which the current flows is constant, the eddy-current loss should vary as the square of the flux, other quantities being equal. Unless the so-called law of electromagnetic phenomena is wrong, the only thing that could have changed is the resistance in the path of the eddy current. Therefore, if the author's separation is correct, after the density reached the value of 8,000 lines per square centimeter the resistance increased, and hence the so-called change in eddy current loss if there was a change in this loss, was produced by a change in the temperature. Thus such a change is not inherent in silicon steel, except in so far as the change in temperature may change the resistance. This fact would seem, possibly, to be the explanation of the change. The change, however, is larger than one would expect from such a source, and I personally believe that the major portion of the change attributed to eddy current loss is due to the fact that the method employed in separating the eddy-current loss from the hysteresis loss would not bear close analysis.

L. T. Robinson: I have only a few words to say about Mr. Wooldridge's paper, they are along the line of Dr. McAllister's remarks, but at the same time I think no matter what way you look at it there is something in his paper after all. If you proceed along the line of analyzing the paper on the basis of what is wrong with the eddy current determination, there certainly is something wrong. If you reason that because there is some error in that portion of the paper the whole thing is wrong, perhaps, that position is tenable, but to support the facts given in connection with the hysteresis exponents, this work has all been gone over in an entirely different way by others and in connection with my own work. We have been able to show by standard hysteresis loops, determined by ballistic galvanometer readings, that the hysteresis does vary throughout the limits substantially as given in this paper, although I believe the figures in the paper were determined in another way. While I am somewhat familiar with the way in which this work was done, I will not attempt to explain how the figures were arrived at, as Mr. Wooldridge will prefer to cover that when he closes the discussion.

There is, however, one point about these eddy currents which is of great importance, and which I do not think is fully appreciated; one which should not be neglected by research engineers and physicists until it is straightened out, that is, while the production of eddy currents and the way in which they are connected to core losses is theoretically covered in a certain way, these theories must be very incomplete, and inaccurate. We know by separation at fixed densities, with varying frequencies, what has always been considered to be a legitimate method, that we do get results substantially as shown in this paper, and we also know that these results cannot be thoroughly understood until we have some more complete theory to account for the discrepancies found.

In connection with the subject of eddy losses we have another fact which does not show anything except the incomplete state of our knowledge on this point, that is, we have silicon iron referred to in this paper which has a resistivity of approximately five times that of ordinary iron. We also have numbers of tests on transformers which show the eddy losses at a given density in a similar transformer have varied about in the proportion of 1 to 2.5 or 3. On the basis of any theory which has so far been brought out, the eddy current should be a direct function of the resistivity, and until we can in some way measure what it is that goes wrong and why it is that the results are so absurdly different from what the resistivity values would indicate, we should not be satisfied. I simply take this opportunity to present this as one of the problems that ought to be of interest to the pure physicist. Of course, it is of engineering interest too, but it is of such absorbing interest that I cannot see why the physicists who are practicing research work for scientific information alone have not tackled the problem with more strength, I certainly hope that something will be done that will lead to a solution of it, and that we may get the explanation of why, as Dr. McAllister says, "things are not the same as it seems that they should be."

George F. Sever: The paper by Mr. Hendricks I consider as one of great value to those in the educational field. Professors in the different colleges and universities have been testing insulating materials with every known apparatus, either as they have built them, or else bought them from the various manufacturing companies. They have placed a great deal of dependence on the spark gap method, either that which has been developed by Dr.

Steinmetz and advocated in the Institute Standardization rules, or that recommended by Mr. Fisher, as presented at the International Electrical Congress at St. Louis. Other professors have used the ratio method, measuring the voltage on the primary and trusting that the ratio between the primary and secondary held for all loads and all conditions and have reported to their clients that the breakdown voltage on these materials had a certain value. The sizes of the test plates have been different at different laboratories, and have given different results, so that material which was tested at one place, if we were sure it had identical construction, when taken to another place would test out at a different value, so that the whole situation seems to have been and probably is to-day very chaotic. While talking with the representative of the Electrical Testing Laboratories a few days ago he stated that the results they secured with plates of different forms and sizes gave entirely different results for the breakdown of insulating materials, because the voltages may not have been measured correctly or there were some other conditions in the problem. Now, if the results of Mr. Hendricks' investigations are correct, we will have a perfectly uniform method for the measuring of voltage on high tension work, and I think his paper will lead us in that direction and a final and definite method will be available for incorporation in the Standardization Rules.

Some time ago I wanted to measure high voltages at Columbia and was able to use a condenser method. Later I found the condenser method used up to certain voltages at the works of the General Electric Company, and I want to ask Mr. Hendricks if the condenser method could not be made a standard method, using two or more condenser plates in series and measuring the drop with a static voltmeter across one or more plates, as the conditions required; there have been condenser voltmeters built, and employed successfully. I would like to hear a discussion on the possibility of using condensers in series, the plates being of small size so as not to disturb the circuit too greatly.

I would like to ask if this method which is proposed is applicable to all voltages from the lowest, say 10,000 volts, which sometimes has to be used, up to 400,000, which seems to be the typical voltage indicated in Mr. Hendricks' paper. Cannot we use some simpler method for the lower voltages, say up to 50,000? You must remember that universities which sometimes have to teach high-voltage experimentation, do not have all the necessary funds for building or purchasing high-tension apparatus. If there is any other simple method, which does not cost too much for the universities to indulge in, I as one of the Professors would like to know about it.

J. R. Craighead: The real purpose of laboratory investigation of insulating materials is to secure data which may be applied to the design of insulated apparatus. Any satisfactory method of test used in the laboratory must therefore furnish results which are directly comparable with those obtained by tests on installed apparatus. The use of voltage as the connecting standard would be satisfactory if a statement in terms of voltage applied meant the same insulation strain in both cases; but it frequently does not. Mr. Hendricks, for instance, speaks of limiting the wave of a generator to practically a sine by using a special generator and then by not overloading the generator beyond certain limits. Now, that is usually impracticable when you come to apply it to a large installation, such as testing cables on a city circuit. There the testing outfit is usually so designed that the maximum capacity of the transformers must be used to carry simply the testing load. This means that a certain variation from a proper wave shape is unavoidable in these practical tests.

With respect to the control of the apparatus, we meet another difficulty. The control of the apparatus by the generator field would be a perfect method if it could start from zero and go up to an unlimited quantity. But it cannot. It generally must start somewhere around 50 per cent of the full voltage of the generator. That presents difficulty in practical tests of large cable systems, for the reason that when you close the main switch on a cable system you throw a heavy capacity load on the testing outfit, and in some cases the voltage of the generator at once jumps up to much more than 50 per cent of normal, and there is a first increment of such size as is dangerous to the system. To meet a condition like that, it is possible to use an induction regulator, which can be arranged to buck or boost voltage, so that with a given generator the voltage can start at zero and run through any gradation to the highest limit specified. At the same time the induction regulator has considerable exciting current and some impedance, and the result is a certain distortion of wave shape, which need not be excessive, but which must always be reckoned with. Since these distortions of voltage wave form may cause differences in the stress on the insulation without changing the indication of the voltmeter, the voltmeter is not a satisfactory primary standard to connect tests made under widely varying conditions. Such a connecting standard should be practically independent of the usual changes of voltage wave form, giving a result under all conditions which depends directly on the stress on the insulation, rather than on any special function of the voltage. Up to date this primary connecting standard is the spark gap.

The spark gap is by no means perfect. I do not need to go into its difficulties. They have been taken up; but at any rate we are measuring a length with the yard stick when we measure the insulation strength of material by comparing it with the insulation strength of a known material, that is, air. The qualities of the materials are not strictly the same, but for the present it is the best we can do, and is an effort in the right direction.

Consequently, all we can ask is that some one should provide a better standard than this, and the better standard must be associated not with the idea of how much voltage a thing can stand, because the standing of voltage means a great many different things of different kind, but it must mean a comparison of dielectric strength with the dielectric strength of some known material and the simplest and best known material is air.

In respect to the measurement of the voltage as a secondary standard the volt coil certainly works well, but where the voltages are not too high a potential transformer may be used on the high potential side; we are then enabled to take the voltage directly where it is applied, instead of at a point back in the circuit with more or less uncertain components between. This potential transformer can be made with practically any accuracy desired.

J. L. R. Hayden: The curves on Fig. 1 of the paper on hysteresis and eddy current exponents of silicon steel are very interesting and startling.

That the Steinmetz law of hysteresis does not hold for very low densities has been shown already by Dr. Steinmetz in his original paper. A decrease of the hysteresis coefficient at high densities has been observed repeatedly. Unexpected, however, is an increase as shown in Fig. 1. Further investigations on the cause of this increase would therefore be interesting.

Questionable appears to me the curve of eddy currents. Eddy currents are induced currents and the loss by them is an $i^2 r$ loss and therefore must be proportional to the square of the voltage, and to the square of the magnetic density. An exception could occur only if the resistance changed or magnetic screening took place. With a material of such high resistance as silicon steel this is not probable.

It therefore appears probable that the eddy current losses are so small a part of the total loss as to make their determination inaccurate.

F. M. Farmer: I had a few points that I intended to mention, but most of them have been covered by other speakers. I would emphasize the point Professor Sever brought up about the electrostatic voltmeter. We have used it and consider it successful and satisfactory for moderately high voltages, up to, say, 50,000, where the conditions did not prohibit the use of an instrument measuring mean effective values. I have in mind more particularly the effect and size of the electrodes. Professor Sever has spoken of this point. We are making an investigation now, and the results will be available in the course of a few months but the indications are that the size of the electrode does have a great effect on the apparent dielectric strength of thin materials, such as cloth and paper. The first thought is that when using large sizes of electrodes the electrostatic capacity may affect the wave form. We might get a peaked wave, the maximum of which determines the puncturing value and which is not shown by a voltmeter either in the primary, a voltmeter on the exploring coil of the secondary or an electrostatic voltmeter in the secondary. If we can use small specimens where there cannot be any question of distortion of wave, I do not see any reason why the electrostatic voltmeter would not be satisfactory.

The method involving the use of the ratio of transformation when correctly determined and a voltmeter on the low tension side is also satisfactory.

I would refer to the cup and disk device which Mr. Hendricks speaks of. I cannot see where it has any material advantages over the apparatus most of us are more or less familiar with, using spheres. I believe the sphere device is known as the Skinner apparatus. Mr. Hendricks' suggestion means the use of less oil, but that is not ordinarily of much consequence, and as regards 45,000 volt transformers, instead of 60,000 volt transformers, that does not seem to be a very important point, because if you have a transformer that is good for 45,000 volts, the chances are it is all right for 60,000 volts for testing purposes.

Another point I want to mention is the work of the Committee appointed by the American Society for Testing Materials whose object is the Standardization of Tests of Insulating Material. That Committee is endeavoring to standardize not so much the kind of tests that should be made, but the methods of making the tests. As has been mentioned this afternoon, the whole thing is in a chaotic state. One man gets certain results by his methods and another man gets something entirely different on exactly the same material. It is hoped that the efforts on the part of that Committee to get information along this line will be encouraged by the members of the Institute, and they will give their assistance as far as possible. It is certainly a very important thing, and should be helped in every way possible.

H. L. Schermerhorn: I find in Mr. Hendricks' tests that the areas are rather small. It seems to me while it is very nice to have a fine scientific research made and the results given, of the insulating materials for our electrical apparatus, what we need now is something that is practical. In these days when so many young electrical engineers are coming forward to take up engineering work, without very much shop training, or opportunity to do some of this kind of testing work, they do not have the practical knowledge to take such results and bring them down to a practical basis—what I mean by that is they could not take these figures and use them in designs without serious results. Larger areas and larger number of samples tested under longer time periods give more practical results than the small samples under short time periods. The greater number of tests give very satisfactory results, and often times startling ones to the people who deal with them. The standardization of areas is an extremely important matter, and one which I would advocate the Institute to take up, and fix a standard for, so that all investigators could follow the same definite line.

E. M. Hewlett: The paper by Mr. Hendricks is more for the laboratory test, as I understand it. We need a quick test for the practical work of the factory, and the spark gap seems to be the most convenient test for us to use. If we could have a new curve giving us the values of the spark gap on the upper end of the curve, up around 500,000 and 700,000 volts, I think that is what we are more interested in at the present time, in connection with the oil switches, etc., so it would seem as though for establishing the values of the spark gap or resistance across the high potential, a voltmeter or oscillograph in shunt with this resistance, and the necessary ground to make the test, could be used, and in that way new values for the spark gap might be plotted.

In reference to the testing of the liquids, that is, oils, etc., while they all break, down at a certain voltage when they are dry and in proper condition, if they are tested for time, there is a great difference. That is not mentioned in the paper. We should remember that there is a great difference in liquid insulation and in solid insulation in bulk, particularly under time test.

W. J. Foster: I had in mind to say a few words regarding the potential wave of alternators. I now hesitate as it has been brought out in the discussion that you can have almost any kind of a wave when you get on the other side of the transformer. I do want, however, to compliment the author on the thoroughness with which he has prepared his paper, and his attempt to have everything perfect, beginning with the potential wave of the alternator. The pictures of alternators that he shows are as comprehensive as the life of the industry. He shows an old high periodicity single phase revolving armature smooth core machine, which, as he says, has a good potential wave, and also the very latest turbine generator type with distributed windings in the field as well as the armature.

A well designed machine has a good potential wave, approximately a sine wave. There is quite a difference in machines designed for the same uses, between one of large capacity and one of small capacity when open slots are used. This is brought about by the fact that the breadth of the slot is about the same for a given potential in the very small machine and the large machine, whereas the air gap is much greater in the large machine. The potential wave is affected by the open slot and higher harmonics corresponding to slot frequency are likely to appear provided we do not take certain precautions. There are two or three ways of securing good potential wave. Such as the proper shaping of the pole face, so as to give the sine distribution of magnetism in the air gap; and looking out for the pitch of the windings rather than to use full pitch. One of the best ways of designing machines, even a small machine, such as would be in demand for testing purposes, is to avoid making the number of slots a multiple of the number of poles, in other words, design the machine for a certain number of poles and drop out two or more. This gives a Vernier arrangement in the super position of the potential waves of the individual coils, and in that way practically as good potential wave can be obtained as any shown by Mr. Hendricks in his paper.

Charles F. Scott: I want to speak a word for the Standardization Code. It is neither an oracle nor an encyclopedia. Many people seem to think if it does not cover everything that there is something the matter with it. There have been two uncomplimentary comments this afternoon. One of them was in the paper in regard to transformers with water cooling, and referred to the temperature specifications and outside air. The conditions are obvious. The heat will be partly carried away by the cooling water and partly by the air in contact with the outer surface, and the temperature will depend upon the temperature of the entering water and the temperature of the surrounding air. The whole matter is one for individual specifications in the case of the particular transformer and not for general specifications in the Standardization Rules. All that the latter attempts to cover are certain principles and certain general conditions. Particular cases, especially when they concern large apparatus in which competent engineers are concerned, are left to the intelligent action of such engineers.

In Mr. Hendricks' paper reference is made to the fact that the present Institute specifications prescribe a uniform insulation test for all parts of the winding of a transformer, although in certain cases, it may be known that one end of the winding or the middle point will be permanently grounded. When the present Standardization Rules were in preparation, I undertook the task of drafting a paragraph covering cases of this kind. Objection was made to it for the reason that when a transformer is built, it may not be definitely known whether it is to be used on a single phase circuit or on a three phase circuit either in star or delta connection, or whether some point may be connected to the ground. Whatever the intention may be, the transformer is liable to be used in some way other than that for which it was intended. Hence, it was found impracticable to prescribe rules which would not be quite complex and liable to misapplication and misuse. It was, therefore, decided to make the general specifications so that they would serve for all transformers and to leave special specifications to the discretion of the engineers in special cases.

The principle involved is indicated in this sentence in the Rules:

> The voltages and other conditions of test which are recommended have been determined as reasonable and proper for the great majority of cases and are proposed for general adoption, except where specific reasons make a modification desirable.

C. A. Adams: I understand that the hysteresis and eddy current losses were separated in the ordinary manner by assuming that the former is proportional to the frequency and the latter to the square of the frequency. But after this separation, how were the exponents of Fig. 1 determined? Also, were the corresponding coefficients determined?

Wm. A. Del Mar (by letter): The subject of dielectric stress in the insulation surrounding a cylindrical conductor has lately given rise to considerable discussion at meetings of the Institute and elsewhere, and particular interest has been evinced in a curious phenomenon observed when dielectrics are subjected to powerful electric stresses, the dielectric acquiring temporarily some of the characteristics of a conductor without suffering any mechanical or physical damage of a permanent nature. This phenomenon was observed several years ago by Dr. E. Jona and again by Professor Alexander Russel, neither of whom offered a satisfactory explanation of it.

In order to fully grasp the significance of this phenomenon, it will be well to refresh our minds with certain well known facts and formulae relating to the quantitative expression of dielectric stresses in cables.

The following well known formula is based upon the assumption that the lines of electrostatic induction extend radially between the conductor and cable sheath and that therefore their density, or, in other words, the dielectric stress is greatest at the surface of the conductor.

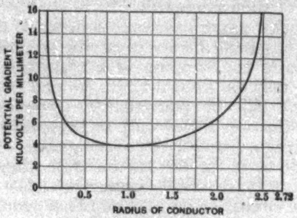

FIG. *A*

$$K = \frac{V}{r \, l n \frac{R}{r}} \tag{1}$$

where K = the dielectric stress at the surface of the conductor when the volts between wire and sheath equal V.

R = outer radius of insulation.

r = radius of conductor.

This equation is plotted as a curve in Fig. *A*. Its physical interpretation was discussed by the present writer after the paper on "Potential Stresses in Dielectrics", by H. S. Osborne in PROCEEDINGS A. I. E. E., December, 1910. Let it suffice to repeat that in the case of cables in which R/r is greater than 2.72, if the conductor were to grow in diameter, the dielectric stress at its surface would decrease until its diameter became $\frac{1}{2.72}$ of the outside diameter of the insulation, after which the stress would increase. If instead of the conductor growing in diameter, the dielectric at its surface were to break down, the effect would be the same. The stress in the uninjured dielectric where it meets the injured part would decrease until the diameter of the injured part equalled $\frac{1}{2.72}$ of the outside diameter of the insulation, after which the stress would increase. If, therefore, the applied voltage is just sufficient to break down the layer of insulation nearest the conductor, the next layers of insulation will not necessarily break down, as the virtual increase of conductor diameter, due to the breakdown of the inner layers, will have eased the stress to a safe value. Hence, as pointed out by Alex. Russel, a partial internal disintegration of dielectric should be possible in such a cable without a complete puncture.[†]

An interesting contribution to the discussion referred to above, was that of Mr. W. I. Middleton, who pointed out that according to equation (**1**), the outside diameter of the insulation may be made a constant entirely independent of the size of the conductor and dependent only upon the applied voltage. Thus, referring to equation (**1**), assume that $\frac{R}{r}=2.72$ so that $r=\frac{R}{2.72}$ and $ln\ \frac{R}{r}$ becomes unity. Then

$$K=\frac{2.72\ V}{R},\ \text{or}\ R=\frac{2.72\ V}{K} \tag{2}$$

This equation was shown by Mr. Middleton and Mr. Henry A. Morss to be amply confirmed by a great number of tests, so that it is in no sense theoretical or speculative; but it will be observed that its derivation from equation (**1**) depends upon the assumption that the inner layers of insulation are in some way broken down without injury to the outer layers. Mr. Middleton, however, said that " as far as Professor Russel's hypothesis that the dielectric near the conductor breaks down and becomes charred, is concerned, I do not believe it. In eight years in the testing room of a cable factory, I have never seen a cable that has shown mechanical change due to excess voltage in either rubber or cambric insulation ".

[†] Prof. Russel's conclusions have apparently been accepted by one of our leading manufacturers, upon whose specifications appears the following sentence: " Higher voltages, although not necessarily causing a breakdown of the insulation, are apt to *strain* it."

Other careful experimenters have said that they have never known rubber to break down mechanically or physically under high dielectric stress when the conditions of the test have precluded a complete rupture.

We are thus led to the anomaly that a formula is arrived at by theory and found correct by tests and then the theory upon which it is based, is apparently denied and contradicted.

The object of this contribution is to suggest an explanation of this apparent inconsistency.

A large number of chemical analyses of rubber compounds shows that there is always a certain amount of moisture present, the amount usually varying between one-quarter and one-half per cent by weight, which is equivalent to between one-half and one per cent by bulk. This amount is doubtless increased during the usual twelve or twenty-four hour immersion in water for testing purposes, so that a rubber compound may be regarded as permeated throughout its mass with minute particles of moisture. This moisture has a very perceptible effect upon the resistance of the compound as measured by the ordinary galvanometer method after electrification for one minute, it being the practice of many manufacturers to boost the resistance by placing the compound in a drying oven for a few hours before testing. This commercial drying process often doubles the resistance of the insulation, showing that moisture is present in sufficient quantities to radically affect its electrical properties. The specific resistance, however, is not the only electrical property affected by the presence of moisture. Rubber compounds usually have a specific capacity of about 2.5, while that of water is about 80, which is 32 times as great.* The significance of this, lies in the fact that when a dielectric of high specific capacity is placed in a field of electric force traversing a medium of lower specific capacity, the tubes of force tend to run through the foreign dielectric, because by so doing the potential energy of the system is decreased. If this dielectric is free to move, it can further decrease the energy by moving from its original position to one where the tubes are more thickly congregated, because the more tubes which pass through the dielectric, the greater the decrease in potential energy. The foreign dielectric will therefore be urged towards the part of the field where the tubes of force are the densest. In the case of the radial field between a cylindrical wire and a concentric sheath, the moisture in the dielectric will therefore be impelled towards the wire, with the result that the inner part of the insulation will become more impregnated with moisture than the outer, the particles of moisture ranging themselves about the core in much the same way that iron filings range themselves near the poles of a magnet. In order to study the effect of this condition, it will be well to refresh our memories about a well known experiment originated

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***If permeated with electrolyte the specific capacity of water will be much greater than 80.**

by Nicola Tesla. If two large conductors *A* and *B* (Fig. *B*) are separated by air, and the maximum possible difference of potentials set up between them, the potential gradient will be approximately represented by a straight line such as *D*. If, however, a piece of glass *C*, be introduced between *A* and *B*, the air will be electrically ruptured. The well known explanation of this phenomenon is, that the glass having a higher specific capacity than air takes a correspondingly lower potential gradient, thereby increasing the gradient in air beyond the rupture point as shown by curve *E*. The specific capacity of glass is about eight times that of air; if it were thirty-two times as great, the potential gradient would be as shown by curve *F*.

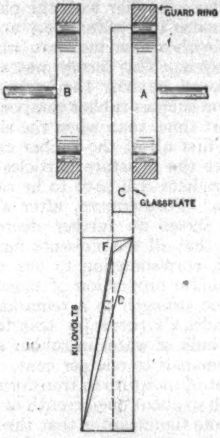

FIG. *B*

In other words the potential of the conductor *A* would virtually be carried to the outer edge of the glass.

This is possibly what happens in the moisture impregnated cable insulation. The potential gradient along the zones of moisture is practically zero, carrying the potential of the wire far into the insulation. The moisture is, however, not continuous, so that the equipotential lines are not concentric with the wire, but consist of a series of attenuated peaks having their minima at the surface of the wire and their maxima deep in the insulation. The inner insulation would therefore be unable to support a potential gradient, as shown by Mr. Middleton's tests, and yet would show no sign of internal breakdown, thus giving rise to the anomaly which has been fruitful of so much discussion.

If this theory is correct, the cable should show practically no increase of capacity when stressed to near the rupture point, as would be the case if the inner layers had been reduced to a conducting state, for the capacity is a measure of the number of tubes of force between the wire and sheath and this will not have materially increased, owing to the small proportion of the total dielectric which is occupied by water particles. That the capacity actually does not materially increase, was shown by careful tests made by Dr. Jona and others; and their results have been confirmed in the course of commercial testing by measurements of the charging current prior to breakdown.* Another requirement of the theory is that the occluded moisture must be free to move within the insulation. That such is the case, is known to those familiar with the phenomenon of water entering negative mains by endosmose,† and is also deducible from the rapidity with which moisture may be removed by means of a drying oven. This theory may also explain the well known fact, mentioned by Mr. Hendricks, that the dielectric strength of insulation such as rubber compound, is greater when electrified for a short time, than when the electrification is prolonged, because at first all of the rubber carries the potential gradient, while after the moisture particles have congregated, almost the entire gradient will have to be carried by the outer layers of insulation. Furthermore, after a certain time, the dielectric strength shows no further decrease, which is explained by the fact that all the moisture finally reaches a position of equilibrium, corresponding to the minimum potential energy. That a minute proportion of moisture has the effect of reducing dielectric strength to a remarkable degree, is well shown by Mr. Hendrick's curve for transformer oil, Fig. 21. The percentage by bulk of water in rubber insulation has been stated to be from one-half to one per cent. The effect of one-tenth of one per cent of moisture in transformer oil, is to reduce its dielectric strength to about one-seventh of its value when dry, and what is even more significant is that the greater part of this reduction is due to less than one part of water in 10,000, the further addition of water having but little effect. Analogy would lead one to suppose that a correspondingly minute proportion of water would effectually alter the dielectric strength of rubber and that additional water would have little or no effect.

It might be objected that this theory does not explain the Middleton phenomenon because the outer limit of the displaced water particles does not necessarily correspond to the radius $r = \frac{R}{2.72}$ and therefore the effect of the water particles would be to give an indeterminate reduction of the effective thickness of insulation. This objection would be fatal were it not for the

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*Alex. Russel, November 7, 1907. Journal I. E. E. (London), Vol. 40.
†Journal I. E. E. (London), August 1908, p. 455.

following fact. By reference to Fig. A it will be observed that the curve A is almost flat for about one-third of its span. In other words, if the insulation be supposed to be divided into three concentric layers of equal thickness, and the outer limit of the moisture particles is anywhere within the middle layer, their effect in reducing the effective thickness of insulation would be practically the same as if they extended exactly to the radius $\frac{B}{2.72}$.

A corollary to be deduced from this is that rubber insulation may be susceptible of internal destruction without puncture, if perfectly dry, but the presence of moisture, even in minute quantities will prevent this action by affording a natural " grading " of the insulation.

The reader is again reminded that all this is mere theory and that experimental work is required to prove or disprove it. It is to be hoped that someone who is well equipped for the work, will undertake the required experiments, as the theory has a practical bearing on the manufacture and use of cables.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, Feb. 15, 1911.

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DESIGN, CONSTRUCTION AND TEST OF AN ARTIFICIAL TRANSMISSION LINE

BY J. H. CUNNINGHAM

A little over a year ago Dr. Steinmetz suggested the construction of an artificial transmission line or " slow-speed conductor " in the Electrical Laboratory at Union College. It was proposed to duplicate or reproduce as nearly as possible the conditions of a high-voltage long-distance transmission line in the laboratory in such a way that the various phenomena connected with a line of this sort might easily be investigated. It was not desired particularly to study the effects of very high voltage but rather to investigate and study the various transient and other phenomena in connection with switching, sudden change of load, etc.

DESIGN

Various methods of reproducing the conditions of a transmission line were suggested and the most satisfactory method consisted of winding wire of suitable diameter on glass tubes or cylinders and lining the cylinders with tin foil. In this way, by selecting the proper diameter of wire and proper diameter of tube, any relation between resistance, inductance and capacity could be obtained. Calculations were therefore made to find the diameter of wire and size of tube that would give the most economical design.

It was at first intended that each unit or cylinder should have constants equivalent to about one mile (1.6 km.) of line such as No. 0 B. & S. gauge conductors spaced five feet (1.5 m.) apart. It was soon found however that to obtain sufficient electrostatic capacity a cylinder of very large diameter (about 10 in., 25.4 cm.) would be required, and the cost of such cylinders was found to be expensive. In view of this fact it seemed advisable to use the half mile instead of the mile as unit. Each unit should have therefore approximately the following constants:

Resistance, 0.25 ohms; inductance, 0.001 henrys; capacity, 0.007 m.f.

The formula used in computing the inductance is as follows:

$$L = \frac{4\,\pi^2\,r^2\,n^2}{l \times 10^9} \times 2.54$$

where L = inductance in henrys.
r = radius of winding in inches.
n = number of turns.
l = length of coil in inches.

The formula used for computing the capacity is as follows:

$$C = 4.54 \times \frac{l\,r\,k}{2d \times 9 \times 10^5}$$

where l = length of tube.
r = radius of tube.
d = thickness of glass.
k = specific inductive capacity of glass.

Using the above formula various combinations of length of tube, diameter of tube, and number of turns and diameter of wire which would give the proper constants were worked out. Prices were then obtained on various sizes of glass cylinders and it was finally decided that the most practicable design called for a cylinder six inches (15 cm.) in diameter, $\frac{1}{8}$ in. (3.1 mm.) thick, $4\frac{1}{2}$ ft. (1.36 m.) long wound with 240 turns of No. 8 B. & S. gauge copper wire.

Substituting these values in the above formula the following constants are obtained. Three inches on each end of tube are left free of winding.

$$L = \frac{4\,\pi^2 \times 3^2 \times 240^2 \times 2.54}{48 \times 10^9} = 0.00104 \text{ henrys}$$

$$C = \frac{2.54 \times 48 \times 3 \times 4.5 \times 8}{2 \times 9 \times 10^5} = 0.00748 \times 10^{-6} \text{ farads}$$

The value used for *k* is 4.5. This factor is rather indefinite, different authorities giving values which vary from 3 to 10. The value 4.5 was taken as an average value and the results of experiments on the line show that this value is probably too high.

The resistance of 240 turns of No. 8 B. & S. gauge wire is 0.24 ohms, at 20 deg. cent. This is the resistance of one-half mile (0.8 km.) of conductor between No. 0 and No. 00 gauge copper wire. With the above design each unit should be equivalent to one-half mile (0.8 km.) of No. 00 gauge wire spaced five to six feet (1.5 to 1.8 m.) apart.

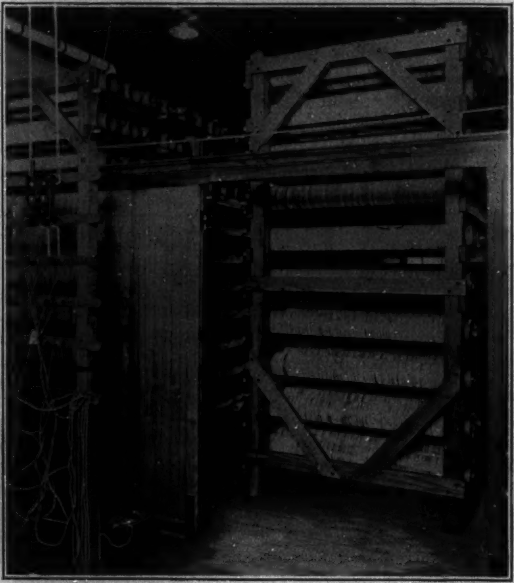
In order to hold the tubes in as compact, safe, and at the same time accessible form as possible, suitable racks were designed. As each tube when complete weighs about 40 pounds, a rack of fairly heavy construction was required. Because of the limited floor space the racks had to be built as high as the ceiling would permit. Each rack, as designed, carried 100 tubes in 10 rows of 10 tubes each. Their approximate dimensions are 9 ft. (2.7 m.) long by 8 ft. (2.4 m.) high by 4½ ft. (1.3 m.) wide. These racks have proved entirely satisfactory.

A single unit

CONSTRUCTION

The wire was placed on the glass tubes in the following manner. It was first attempted to wind the wire directly on the tubes. This was done by passing a rod threaded at both ends through the tube and clamping it in place in the centre of the tube by means of blocks at each end. Because of the uneven manner in which the ends of the tubes were cut off this method of clamping set up stresses in the glass which broke the tubes. Felt pads were tried to distribute the pressure more evenly but were not found very satisfactory. This method was finally abandoned. Instead of winding the wire directly on the glass tube it was first wound on a wooden form constructed for this purpose. This form consisted of a cylinder 6½ in. (16.8 cm.) in diameter and

5 ft. (1.5 m.) long mounted on bearings about 5 ft. (1.5 m.) from the floor. A pulley was attached to one end of the cylinder and belted to a shunt motor. There were 230 turns (equivalent to 240 turns on the glass tubes) wound on the forms. The coils were then loosened, slipped off the wooden cylinder, and were then ready for mounting on the glass cylinders. This method proved entirely satisfactory.



A portion of the line

End connections were made by means of a copper strap one inch (2.5 cm.) by 0.025 in. (0.63 mm.) by about one foot (30.5 cm.) long. These strips were soldered to the last turn and formed very convenient terminals.

The solenoids of wire after being removed from the wooden form were mounted on the glass tubes. The loosened coil was slipped over the tube. The copper strap at one end of the wire was then tightly fastened to the tube by means of several layers of one inch (2.5 cm.) by 0.007 in. (0.18 mm.) linen tape, which was afterward thoroughly varnished. The wire was then distributed as evenly as possible over the entire tube, tightened by turning the wire, and made fast at the other end by taping.

The tin-foil lining was placed in the tubes in the following manner. Sheets of raw-hide fibre of 40 mil thickness were cut in strips 54 by 17.5 in. (137 by 44.4 cm.). The tin-foil was then pasted on these sheets of fibre by means of a coating of varnish. A small margin was allowed at each end also longitudinally to prevent the foil acting as a short circuited secondary. Transverse slits were cut at intervals of 6 in., alternately half way across the sheet, to prevent eddy currents. Small copper leads were then soldered at one end of the tin-foil sheet. The chief difficulty in soldering is that if the iron is too hot the tin-foil will be melted. By proper care however a good joint can be made. The sheets of tin-foil were then placed in the glass tubes and the leads connected together by soldering them to a bus. This consisted of No. 8 B. & S. gauge bare copper wire attached to the frame of the rack by porcelain insulators.

The next difficulty was to keep the tin-foil pressed out firmly against the glass tubes. The fibre did not prove springy enough to adapt itself completely to the form of the tube. It was decided to use expansion rings to press the fibre more firmly against the glass. Hard drawn copper wire was first tried for this purpose but did not prove stiff enough, and also showed a tendency to slip longitudinally. Phosphor bronze strips 5/16 in. (7.9 mm.) by 30 mils and ½ in. (12.7 mm.) by 30 mils were finally used. These rings proved quite satisfactory; three were used per tube. By their use the electrostatic capacity of the tubes was considerably increased. Care must be taken in placing the rings in the tubes not to crack the glass. One hundred and fifty tubes were constructed in this way during the spring of 1910, the work being done by Messrs. Becker and Grover, seniors in the Electrical Engineering Department of the University. After some preliminary testing it was decided to continue with the construction and at present the line consists of 400 cylinders.

The line is represented diagrammatically by Fig. 1.

The diagram shows the method of connecting the units together and with sufficient number of units a line of any length could be produced.

CONSTANTS OF LINE

The complete line has the following constants:

Capacity 1.135 microfarads. Inductance 0.3944 henrys. Resistance 93.6 ohms.

The capacity was measured as shown in Fig. 2.

As seen by the diagram, the potentiometer method was used to eliminate harmonics. Also, the tubes were connected in multiple so as to measure the true capacity and not the charging current of the line.

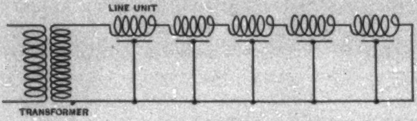


FIG. 1

From the above constants the equivalent length of the line is determined as follows:

In a circuit of distributed capacity and inductance the resonance frequency or natural period is expressed by

$$f = \frac{1}{4\sqrt{L\,C}}$$

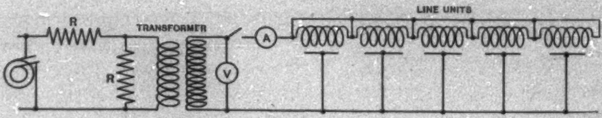


FIG. 2

where L = total inductance in henrys.
C = total capacity in farads.

$$f = \frac{1}{4\sqrt{0.394 \times 1.135 \times 10^{-6}}}$$

$$= 360 \text{ cycles.}$$

Since the propagation of an electric wave is at the same rate as the velocity of light or about 186,000 miles (299,338 km.), per second it follows that the natural period of a line may be represented by the expression

$$f = \frac{186{,}000}{4\,l}$$

where $l =$ length of line in miles.

Substituting for f its value, 360 cycles, gives as the equivalent length of line 130 miles (209 km.).

Since the total resistance of the line is 93.6 ohms the resistance per mile of the equivalent conductor lies between that of a No. 1 and No. 2 B. & S. gauge wire. The artificial line is thus equivalent to 130 miles (209 km.) of No. 1 (approximately) B. & S. gauge wire.

The capacity of the line is considerably less than that expected from the design. This is due to several causes. In the first place the tubes were assumed to be of the uniform thickness of ⅛ in. (3.1 mm.). The tubes actually varied anywhere from ⅛ in. to ¼ in. or ⅜ in. (3.1 mm. to 6.3 mm. or 9.5 mm.). in thickness. This of course greatly reduced the electrostatic capacity. In the design it was assumed that the tin-foil pressed tightly against the glass. In practice it was found impossible to make it do so, there being more or less air space between the tin-foil and glass. Again the specific inductive capacity used in the design may have been too high. If some better means of lining the tubes with the tin-foil can be devised the capacity of the line will be greatly increased.

A great amount of trouble has been caused by the breaking of tubes. After being completed and placed on the racks they would crack with no apparent cause. This breakage was large at first but gradually became less and it now seems that those which are going to break are eliminated.

A summary of the lines is as follows:

Number of tubes in line	400
Capacity of line	1.135×10^{-6} farads.
Inductance	0.3944 henrys.
Resistance of line	93.6 ohms.
Natural period $\frac{1}{4\sqrt{L\,C}}$	360 cycles.
Equivalent length of line $\frac{186000}{4\,f}$	130 miles (209 km.)
Equivalent size of conductor	Between 1 and 2 B. & S.

Tests on Line

The following records show the results of some of the tests that have been made on the line. Three classes of tests are shown; *a*, throwing voltage on the line, *b*, opening the line. and, *c*, switching line on line. The work was all done with about two thousand volts on the line, power being taken from the city lighting circuit.

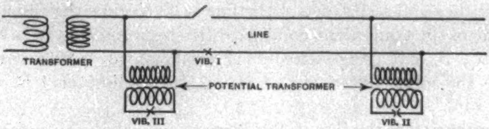

LINE
TRANSFORMER
VIB. I
POTENTIAL TRANSFORMER
VIB. III
VIB. II

Fig. 3

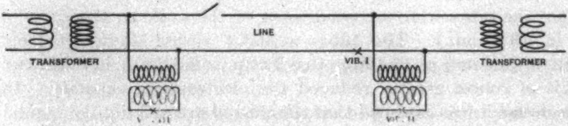

LINE
TRANSFORMER
VIB. I
TRANSFORMER

Fig. 4

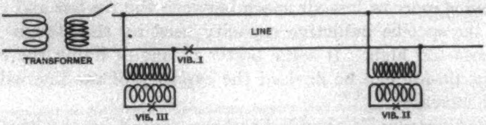

LINE
TRANSFORMER
VIB. I
VIB. III
VIB. II

Fig. 5

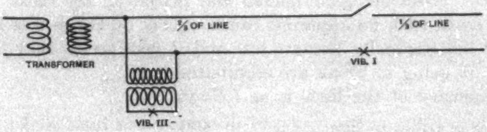
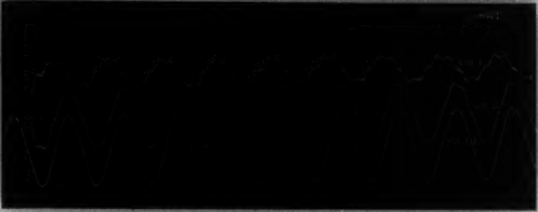

⅘ OF LINE
⅕ OF LINE
TRANSFORMER
VIB. I
VIB. III

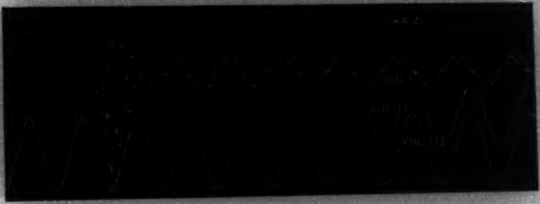
Fig. 6

a. Closing Line. The conditions under which these records were taken are shown by Fig. 3. Voltage was thrown on the line which was open except for a 50-watt, 50 to 1 potential transformer connected across the receiver end. The record shows the voltage at the generator end, the voltage at the receiver end, and the current. In all the records vibrator I is current, vibrator II voltage at receiver end of line, and vibrator III voltage at the generator end of line.

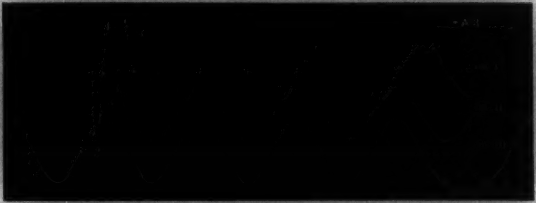
In record *a*-1 the line was closed near the zero value of voltage, and very little surge of current and voltage resulted. In records *a*-2 and *a*-3 the line was closed near the maximum point of the voltage wave, and surges of considerable magnitude both of current and voltage at receiver end result. The rise of voltage at the end of the line with the first rush of current is very noticeable.



Record *A*1



Record *A*2



Record *A*3

b. Opening Line. These records were taken under the conditions shown in Fig. 4 and Fig. 5. In records *b*-1 and *b*-2 the line was opened at the generator end while feeding into a transformer at the receiver end. The current was measured at the receiver end of the line. When disconnecting switch is open the

Record *B*1

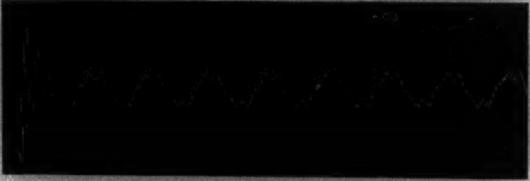
Record *B*2

Record *B*3

line is entirely open at the generator end. Before opening the line the record shows the charging current of the transformer (vibrator I), voltage at generator end (vibrator III), and voltage at the receiver end (vibrator II). When line was opened the low frequency surges of voltage and current are shown. These surges are seen to be of decreasing mangitude and of longer and longer duration. The voltage wave is very flat topped, and the current wave peaked, the peak occurring at the reversal of voltage.

Record *C*1

Record *C*2



Record *C*3

In record *b*-3 the line was opened with only a potential transformer across the receiver end. In this case, however, the potential transformer at the generator end was connected on the line side of the disconnecting switch, and the current measured at the generator end of the line. After the line is opened we have a closed circuit consisting of the line and potential transformers. Before opening the line the record shows the charging current of the line (vibrator I), voltage at generator end (vibrator III), voltage at the receiver end (vibrator II). When line was opened we see again the low frequency surge of voltage and current.

c. Switching Line on Line. The conditions of this test are shown by Fig. 6. Two-thirds of the line was alive and records of the current were taken as the remaining third of the line was thrown on. In this case the dead line received the initial charge from the live portion of the line, and a high frequency oscillation takes place. It is interesting to note the difference between these records (*c*-1, *c*-2 and *c*-3) and the records of the current when the whole line was thrown on a transformer (*a*-1, *a*-2 and *a*-3).

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

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PROTECTION OF ELECTRICAL TRANSMISSION LINES

BY E. E. F. CREIGHTON

INTRODUCTORY SUMMARY

A review of some of the principal headings with an occasional comment will give a rapid survey of the scope of this paper. The conditions of single grounds occupy most of the treatment, although incidentally the subject of short circuits and high frequency oscillations are brought in briefly where they are particularly pertinent. The general principles of the *arcing ground suppressor* are described. Its mechanical features, consisting of an oil switch, electrostatic or electromagnetic selective relay, and safety auxiliary devices, are treated in detail. Then follows a discussion of the security with a metallic ground and the practical tests of the *arcing ground suppressor.* The electrostatic capacities of the line wires are so changed by the accidental grounds, that considerable space is given to this subject under the three heads of analogy, physical theory, and mathematical solutions. This subject has a strong bearing on the design of the *suppressor* but has only a convincing and theoretical connection with the use of it. In connection with the arcs on lines, tests are given of arc length, voltage, and currents. These are illustrated by simultaneous photographs of arcs on horns and oscillograms with curves of subsequently calculated lengths, voltages, and currents.

The second part of the paper involves a general discussion of protective problems on transmission lines. The terms " super-spark potential " and " bolt-peak " are defined. Some new theory on lightning induction on lines is given. The following head lines show the nature of the discussions: Possibilities of using lightning arresters to protect against the "bolt-peak;" trolley line arresters; why "spill-overs" occur usually on only one insulator; numerical conceptions of the factors of induced lightning; some observations on direct strokes and their effects; where lightning will strike; what has been done to protect lines; tests of overhead grounded wires; protection by high dynamic potentials and chance; protection by corona; line construction and design from the singular standpoint of protection; conditions without the arcing ground suppressor with several photographs illustrating arcs on insulators; and finally illustrations and theory on the burning off of line wires by the electric arc.

The object of this paper is, primarily, to describe a new method of protecting line insulators against arcs to ground and the consequent vicious surges which accompany such accidental arcs, and to describe the apparatus for accomplishing this, with statements regarding its scope of application and its limitations;

Secondarily, to point out the trend of the developments in line protection, to record some experimental data relating to the problem of line protection, and, with the experience of the laboratory in mind, to speculate on certain lightning effects.

In the past considerable attention has been given to the protection of electrical apparatus. For the protection of medium- and high-tension apparatus, the aluminum arrester has had sufficiently long use to attest its undoubted value. There has, however, been no type of arrester developed suitable to the protection of line insulators and judging from our present knowledge of lightning phenomena, there is little prospect of such a development being made. In general, arresters are not suitable for line protection. Even the relief gap in the form of horns at the insulator has proved unsuitable and ineffective. There is nothing offered yet which does not involve an interruption of service when an accidental arcing to ground takes place, as well as permitting surges of high frequency and of considerable energy to play at will in the system.

In the foregoing statement that lightning arresters are never recommended specifically for the protection of insulators, the use of arresters on a trolley line is an apparent contradiction. The statement, however, is true. A further discussion is given later under the subject of protection of trolley lines.

Line Protection. The problem of line protection may, for present purposes, be divided into two parts:

First, the suppression of the arc that follows a lightning discharge over an insulator from one phase to ground. This phenomenon is the most frequent one. Apparatus is described which suppresses such an arc. It is immediately adaptable to lines on which the insulator pins are grounded—a condition which exists naturally in the use of iron towers.

Second, the prevention and suppression of short circuits between phases. This phenomenon occurs relatively rarely. Some suggestions are made later in regard to this problem, but there is not space at present to describe the work in this field. This paper has to do mostly with the first division of the problem, namely, a single grounded phase.

Circuit Changes During the Process of Grounding. In the following discussion a three-phase circuit only is considered. If the neutral were grounded through no resistance, the result of an accidental ground on one phase, would be a short-circuit of the Y leg of that phase. This short-circuit would necessitate an interruption of service, therefore, we need not consider such practice at the present moment. If the neutral of the three phases is non-grounded or grounded through a relatively high resistance, then one phase may be accidentally grounded or purposely grounded without affecting the operating voltage between phases either delta or Y to any appreciable extent. The whole system becomes unbalanced electrostatically relative to the ground and auxiliary currents will be superimposed on each phase to satisfy the requisite conditions of electrostatic charges. Since the charging circuit of a line is small in comparison to the power current, except in very long transmissions, the drop of potential due to the flow of the charging current along the line is of negligible value. To begin with, the usual condition then,

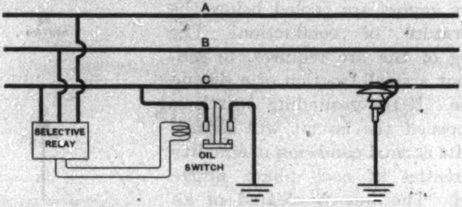

FIG. 1.—Line arcing insulator, switch, and selective relay

is assumed; that is, that a line wire has practically the same potential above ground throughout its entire length, no matter what that potential may be. Later the exceptional cases will be considered.

General Principles of the Arcing Ground Suppressor. A three-phase transmission line under normal operation has its three phases, *A*, *B*, *C*, respectively at an equal effective potential above the earth. If, however, one phase is accidentally grounded as shown in Fig. 1 the potential of that phase above ground will be reduced to the effective potential drop along the arc. If this phase *C* has attached to it a single phase switch *S* which will connect it to ground, the wire will be reduced to ground potential and the arc around the insulator will be extinguished by lack of potential, *i.e.*, shunted out.

The insulator reassumes its normal condition of insulation as soon as the arc vapors are cooled below the temperature of conduction. The chilling of the arc requires, in general, but a small fraction of a second of time. If the grounding switch is now opened the circuit will assume again its normal condition of equality of potential of each phase above ground. The line is cleared of an arcing ground without interrupting the service.

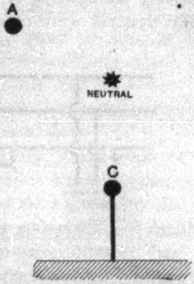

FIG. 2.—Three phases, one grounded and neutral

Before the phase *C* was grounded the neutral of the three phases was at zero or ground potential. After the phase was grounded, the neutral was at Y potential above ground as indicated in Fig. 2.

This is essentially true as the generator produces the same voltage between terminals. This means also that the two other phases, *A* and *B*, are now raised from Y to delta potential above ground.

Selective Relay. Between the phenomenon of the arcing ground and the closing operation of the single-pole switch there must be an intermediate device which picks out the phase that is grounded and closes the proper relay to operate the single-pole switch. Since the most evident and stable condition attending this accidental ground is the decrease in potential of the phase *C* toward ground and the increase in potential of the other two phases above ground, it is natural to choose these factors to operate the selective device. In passing, it might be noted that this device cannot be operated thus independently on each phase but the three phases must operate conjointly in the selective device. In other words, if the line is not in service, and therefore all three phase at zero potential, there must be no movement of the selective device, any more than there is when all three phases are equally charged to an effective potential above ground. This selective operation is attained by connecting the three phases together mechanically. The two devices developed for this purpose are shown in Figs. 3, 4, 5 and 6.

Electrostatic Selective Relay. In Fig. 3, the circuit connections are shown for the electrostatic selective relay. Three insulators are set at angles of 120 deg., facing each other in a horizontal plane. The pin of each insulator is insulated by being fastened to another insulator and connected respectively to the three phases. The electrostatic field produced at the heads of these insulators act mechanically on three aluminum plates placed in front of them and grounded as shown in the photograph Fig. 4. These three aluminum plates are connected together by three light radial rods. At the center, these three rods connect to the bottom of a pendulum, pivoted at the top so that it can swing in any angle away from the vertical. This gives a balanced mechanical system which remains stationary for all voltages so long as they are equal. If, however, as in the case

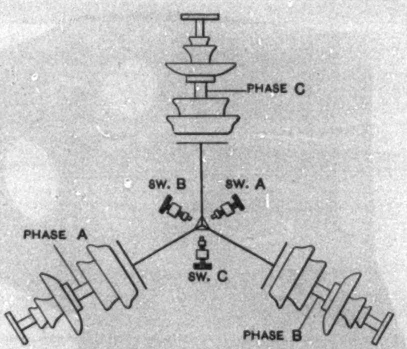

FIG. 3.—Diagram of electrostatic selective relay

assumed, phase *C* is grounded, the electrostatic force on the corresponding aluminum plate is weakened and on the other two plates strengthened. The result is that the pendulum moves over against the contact, marked *S C* in Fig. 3 and clearly shown in form in Fig. 4. Making this contact operates the trip coil on the single-pole oil switch, indicated in Fig. 1. This electrostatic selective relay is easily adapted to all high voltages, but the forces drop off so much for low voltages that it is there found necessary, so far, to resort to potential transformers and electromagnetic coils. The potential transformer is an item of added cost but is not a serious matter at low voltages.

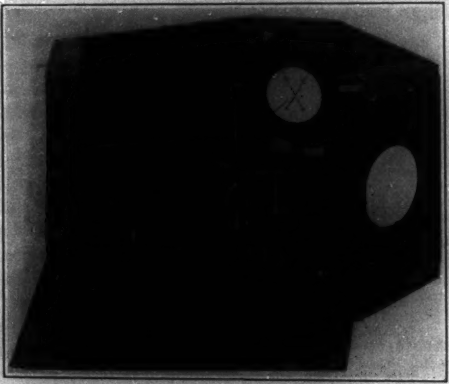

FIG. 4.—Electrostatic selective relay

The Electromagnetic Selective Relay. Fig. 5 shows a diagrammatic sketch of the connections. Three potential transformers *T A*, *T B* and *T C* are connected in Y and the neutral is grounded. The secondary of each is connected directly to a solenoid. The solenoids stand in a vertical position and each has hung over it a core of iron suspended to a three-arm lever pivoted at the center. Just above each lever is a contact point which, when closed, trips the single-pole grounding switch corresponding to the phase. The operation is the same in principle as the electrostatic relay. If the potential on the leg *T C* weakens, the other two phases strengthen; there is a corresponding movement of the cores in the solenoids which results in the desired selective action by closing a contact.

Safety Auxiliary Devices. These devices consist of damping resistance in connection with the switch, interlocks between the three independent single phase switches, and an interlock on the selective relay, as an extra safeguard against closing two single phase switches at once. These devices will be described in order.

Damping Resistance for the Switch. Every circuit containing inductance and capacity is subject to electric oscillations when an arc takes place in any part of the circuit. Where capacity predominates the arc current is seldom continuous. The current starts suddenly, and stops suddenly an indefinite number of times per cycle of the generator, according to the values of the following factors: gap length, current, potential, circuit conditions, air currents, etc. Each time the arc makes or breaks, an electric impulse is given to the circuit which sets up an oscillation. This oscillation is at the natural frequency of the circuit or multiple thereof, and its duration depends on the amount of damping, or rate of absorption of its energy. The danger from such an oscillation lies in resonance with some local circuit, such, for example, as an internal coil in a transformer, generator, potential regulator, etc. The typical behavior of

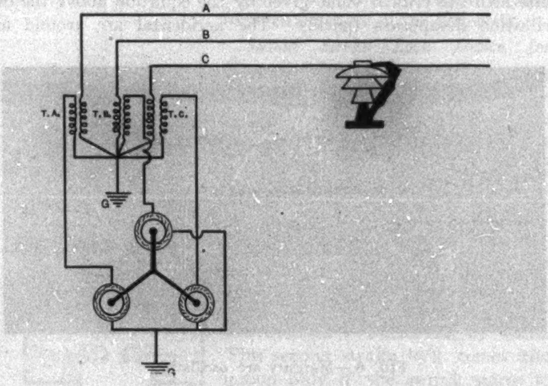

FIG. 5.—Diagram of electromagnetic selective relay

such an oscillation is shown in Fig. 6. This is the natural oscillation in a mercury arc rectifier circuit. Its natural period is 3,000 cycles per second. If an accidental arcing ground took place on this circuit which happened to have a period of 3,000 cycles, it would resonate with the transformer coils and a rise in resonant voltage would result.

Resonance implies repeated impulses or oscillations. If the arcing ground has a resistance in series equal to the critical value given by the equation $R = 2\sqrt{\frac{L}{C}}$, each single impulse will die out without oscillation. Even if the resistance is only one-fifth the critical value given by the equation above the oscillation disappears quickly. The accidental arc around an insulator is extinguished as quickly as possible by the switch: it is then necessary to extinguish the arc to ground in the switch as it opens. To eliminate the dangers from oscillations, damping resistance is placed in the switch pot. This resistance is thrown in series as the switch rod moves out. Fig. 7.

FIG. 6.—Mercury arc oscillation

Interlock Between Switches. The three single-pole switches of the suppressor are provided with a common interlocking device operated by a solenoid, which prevents any two switches from getting in the closed position simultaneously and thus causing a short circuit. In the test, all three trip coils were closed simultaneously but no switch closed. If, however, one contact preceded the others by a small fraction of a second the corresponding switch closed and locked the other two open.

Interlock on the Selective Relay. As a further precaution against accidental short circuits in the switches, the natural conditions of construction of the relays make it impossible to close two trip-coils simultaneously. The three contact points on the selective relay, which are connected to the trip-coil, are so widely spaced that the pendulum cannot swing against two at the same time.

In the case of a double ground the selective relay can be either made inoperative or made selective of one of the grounds. The selective relay, as shown in the preceding illustrations, is inoperative on short circuit of either delta or Y. The pendulum swings between contacts of the trip-coils.

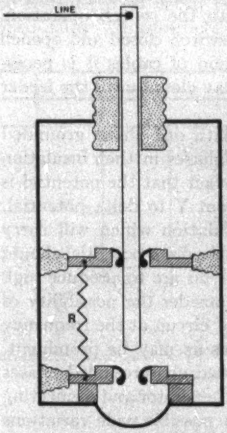

Fig. 7.—Damping resistance in the switch pot

Second Stroke Lock Device for Punctured Insulators. So far, an arc around an insulator has been considered. In this circumstance the protecting switch closes, and opens automatically a fraction of a second later. If, on the other hand, the insulator is defective and punctures, the line potential will reëstablish an arc to the iron pin. This will cause the switch to close again. This second time it is locked shut until the attendant opens it by hand. This second stroke lock comes into action only if the switch starts to close the second time immediately after the first time. In other words, if the switch stays open for a fraction of a second after the first stroke, the second stroke lock becomes inoperative. With the arc shunted out, the dangers from arcing ground surges are avoided. The system can continue to operate with a metallic ground until the fault is located and the faulty line cut out. The chief source of danger in such operation is in the possibility of a second stroke of lightning establishing another arcing ground on another phase before action is taken to clear the feeder.

Arcing Ground Suppressor for Cable Systems. When the insulation of a cable fails, the damage is permanent. The distance from the conductor to the metallic sheath is so small that the normal impressed difference of potential is sufficient to reestablish an arc, even if it were automatically extinguished. It is seldom indeed that an accidental arc is established in a cable from conductor to conductor. Two weak spots seldom fall together. The usual case is a failure of one conductor to the sheath. When this occurs there is nothing to be done but ground the faulty phase to the sheath and thus extinguish the arc. This will prevent the arc to ground burning the insulation into an adjacent phase, melting up everything in the neighborhood with a power arc, and, by the explosive action of the arc, blowing up the surrounding conduit or manhole.

The foregoing requirement simplifies the switch operation. In the protection of an insulator, the switch closed and opened again automatically. For the protection of cables it is necessary for the switch to close once and stay closed until the feeder has been cleared.

Security with a Metallic Ground. With one phase grounded the factor of safety on the other two phases in their insulation to ground is somewhat reduced by the fact that the potential is increased 73 per cent—the increase from Y to delta potential. Since every cable should have an insulation which will carry double delta potential, the increase to only delta potential should not produce a serious strain. There is no arc to produce high frequency, therefore, there is left to consider the possibility of obtaining resonance in any part of the circuit at the frequency of the generator and of such harmonics as may be prominent. The capacity current flowing into the two non-grounded phases must pass through the inductance of the generator and connecting transformers. Taking into account the possible wide variations of inductance and capacity in all systems, one is forced to acknowledge a chance of obtaining resonance with a phase metallically grounded, but resonance in itself has no terrors. The increment of energy in the resonant surge is always small relative to the energy given out even by a small transformer. If a transformer, for example, is loaded even with a few lamps, the resonant potential will be held down by the absorption of the energy of the surge in the lamps. If, on the other hand, the transformer is not loaded and it is in a condition of resonance, its resonant energy will be absorbed by some parallel loaded transformer. When the possibility of resonance internally between coils of a transformer is considered it can be stated positively I believe that there is none.

The natural frequency of a local surge between coils is invariably too high to resonate with the frequency of the impressed potential from the generator. As an example, a 350-kw. 11,000-volt transformer has a natural frequency internally around 90,000 cycles per second. An arc-light transformer has a natural frequency around 3,000 cycles per second. These two examples show such high values of frequency that there is no apparent danger of bringing it within the range of generator frequency.

There are special and unusual conditions which need not be considered in detail here. Such, for example, as unloaded open-delta transformers coöperating with an accidentally broken line wire. The operation with open delta is decidedly bad practice, from a protective standpoint, and should be used in general only in emergencies. At any rate, the prevention is always to keep some load on the transformers or circuits.

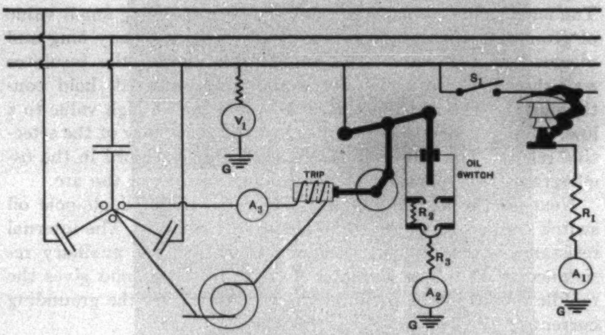

FIG. 8

As a further and final safeguard against possible rises in resonant voltages when a phase is metallically grounded, a reasonable amount of resistance can be kept in the circuit to ground. This resistance will absorb the resonant energy if it appears. There is a limitation set on the amount of resistance by the permissible $I R$ drop. The $I R$ drop must not be such as to reëstablish the arc at the fault.

Practical Tests of the Arcing Ground Suppressor. The general scheme of connections for the analytical testing of the arc suppressor is shown in Fig. 8. The tests were made on a line of the Schenectady Power Company, 21 miles long. The delta potential is 33,000 to 35,000 volts at 40 cycles.

Commencing at the right in Fig. 8 the switch S_1 completed the circuit through the defective insulator, the series resistance R_1 and the oscillograph vibrator A_1 to ground. The insulator was made defective by means of two small wires from cap and pin respectively which were held within sparking distance of each other. The arc would form and burn the fine five-mil wire into a full length arc. With considerable resistance in series with the arc the latter was quite unstable. Since there was no apparatus on the line there was nothing but the inductance of the step-up transformer to aid in making a stable arc. The small value of capacity and the corresponding small value of grounding current prevented the formation of any long and vicious arc. However, the gap length around the insulator was shortened until the arc would, when started, hold continuously. The resistance R_1 was varied from a high value to a low value in order to test and adjust the sensibility of the selective relay. The ammeter A_1 gives the upper record in the oscillograms that measure the grounding current of the arc.

Next to the left in Fig. 8 is represented the single-pole oil switch connected to the same phase and ground. The internal resistance in the oil pot is shown as R_2 and the auxiliary resistance as R_3. The ammeter A_2 next to the ground gives the middle record in the oscillograms which measure the grounding current of the switch.

Next to the left is represented the oscillograph voltmeter V_1 between the same phase and ground.

On the left the selective relay is represented diagramatically with its intermediate connections to the trip-coil of the oil switch. An ammeter A_2 gives a record in a later oscillogram of the current in the trip-coil circuit.

Referring to Fig. 9, oscillogram 8, time is reckoned in cycles, with the number placed just above the points of interest on the records. The instant that the arcing ground commenced (see upper record) is taken as zero time. The current started at the peak of a wave. There is no rush of current into the capacity of the line because a high series resistance was placed in circuit with the arcing insulator. This resistance was used primarily to prevent a large drop of potential between this phase and ground, in order to test the sensibility of the selective relay. This is

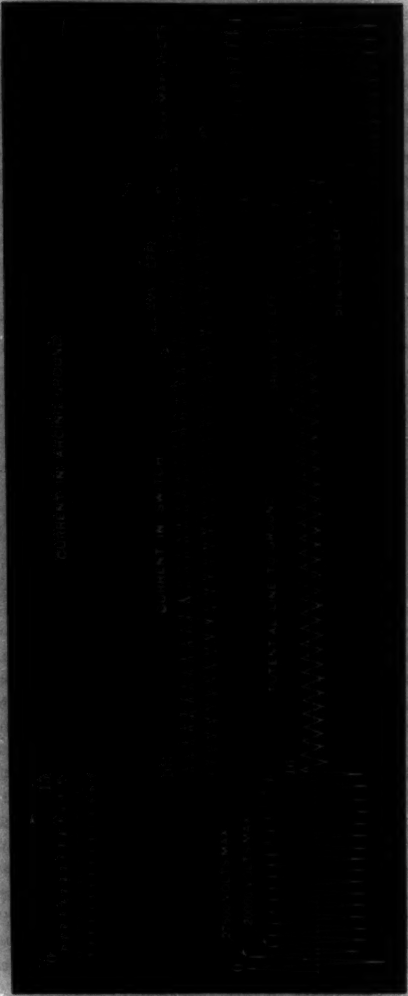

FIG. 9.—Oscillogram 8 on test of arcing ground suppressor

demonstrated on the lower record. The voltage from line to ground drops from normal 27,500 volts maximum at zero time to 20,000 volts at the end of a half cycle. This is 27 per cent drop only or 73 per cent of full potential. It represents the condition of an arcing insulator situated hundreds of miles from the generating station.

Following along the upper record, the arcing ground is extinguished in 15½ cycles. The arcing ground is not reëstablished.

In the middle record, the current in the switch, which shunted out the arc to ground, commences with a rush at 15½ cycles. This current rush is due to the fact that there was less resistance in series with the grounding switch than there was in circuit with the arcing insulator.

During these 15½ cycles of arcing ground, the selective relay moved over to its proper contact, the current was applied to the trip coil of the switch, the plunger moved up and tripped the latch, and the switch rod moved down to its first contact. The proportional time absorbed by each of these phenomena is not measured here, although a partial separation is made in a later oscillogram.

Referring to the lower record, it may be noted that the switch rod strikes the contact connected with the internal resistance two cycles (15½ to 17½) before it reaches its home contact. When the switch rod reaches its home contact the potential from line to ground does not drop to zero in this case because an extra resistance of about 1000 ohms was left in series with the switch.

Referring to the middle record, the oil switch remains closed from 15½ to 55¾ cycles, practically one second. When the current ceases in the oil switch it happens that it leaves the potential of the corresponding phase at a value different from what it should have in a balanced non-grounded condition. The oscillogram indicates in the lower record that the potential should have been a negative peak value but was actually about zero; consequently when the generator changed from a negative peak to a positive peak it carried the potential to nearly double value (52,000 volts maximum in the 56th cycle). In the following cycle the electrostatic unbalancing of the system partially adjusts itself, and in the next following cycle, the 58th, the three phases are symmetrical with the zero or ground potential. This adjustment to a balanced condition seems to take place through the resistance of the voltmeter.

Reviewing the information given by this oscillogram, the arcing ground was extinguished by the protecting switch in 15½ cycles, thus suppressing the resulting surges. The oil switch then took a second to open and clear the circuit. During this test and all others on this line a needle gap was maintained between phases (33,000 volts) but at no operation of the switch did the gap, set at 45,000 volts, spark. When the line was switched on or off, however, the gap would invariably spark. The freedom from surges was obtained by using series resistance, already referred to.

In Fig. 10, oscillogram 9, the principal feature of the record lies in the fact that the relay was made more responsive and cut down the time of arcing ground to eleven cycles. During these eleven cycles the lengthening of the arc around the insulator can be traced by the increase in voltage from line to ground through the arc as shown in the lower record. The potential drops to 19,350 volts at the beginning of the arc and rises gradually to nearly full Y voltage again. Since the potential from line to ground is only slightly disturbed, it is evident that no vicious surges of the system as a whole could result.

FIG. 10.—Oscillogram 9 on test of arcing ground suppressor

In a subsequent test the voltage drop from line to ground was only 11 per cent. The relay was adjusted not to respond. It seems undesirable to have the selective relay too sensitive for fear it might respond to some single-phase Y overload. It can be made non-responsive to the particular unbalancing of phases due to a single-phase delta overload.

Fig. 11, oscillogram 26, shows on its upper record the current in the selective relay and trip-coil circuit. The selective relay required about four cycles to close after the arc started (shown by the drop of potential on the lower record). Initially there was one little rebound of the relay contact (shown in the upper record) and then a gradual, although variable, building up of the direct current. The variations are due, in part, to the line drop when the motors attached to the switches started up.

Fig. 12, oscillogram 33, was taken at a higher speed to show the harmonics in the ground current. There was a poor contact which caused some sparking. These sparks set up extra oscillations superimposed on the harmonics.

Fig. 13, oscillogram 35, was taken with the expectation of showing the second lock shut operation of the switch, but the film was not quite long enough to record the second closing. Instead of using an arc around an insulator, metal electrodes set a little below spark potential to ground were used, so that the arc would restrike after the first extinction by the suppressor. Some other circuit conditions were also changed; the deflection of the current in the arcing ground was increased and the resistance in series with the arc reduced to a small value. The effect of this is shown by the low potential from line to ground (3800 volts) on the lower record during the arc. Also the external resistance in series with the grounding switch was reduced to zero. When the switch rod reaches its home socket, the potential to ground is reduced to zero. The internal resistance in the switch pot delays this reduction for two cycles after the arc is extinguished and again raises the potential through the pot resistance two cycles before the switch opens and restrikes the arc. The records are so similar to the previous ones that no further comments are necessary except perhaps to draw attention to a surge of ground

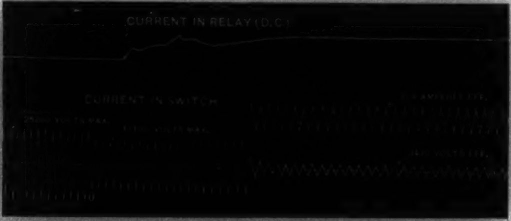

Fig. 11.—Oscillogram 26 on test of arcing ground suppressor

current of 13.7 amperes (3.6 times normal) in the arcing circuit (upper record) at the moment of restriking the arc. The deflection passed through both the other records and nearly reached the bottom edge of the film. This current rush was due to the electrostatic charging current of the line when connected at nearly the peak value of dynamic potential with only a low resistance in series. This is the effect which usually starts the disastrous phenomena of arcing grounds. The voltage from line to ground at this instant (lower record) shows a rise of potential for an instant to nearly normal value, when the grounding arc struck again.

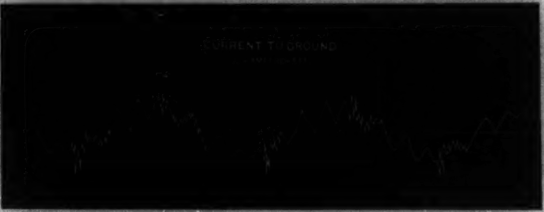

FIG. 12.—Oscillogram 33 on test of arcing ground suppressor

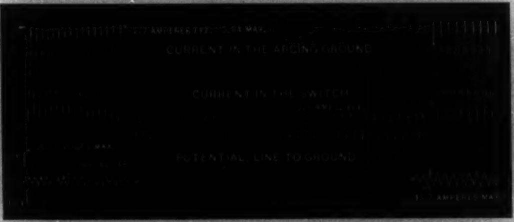

FIG. 13.—Oscillogram 35 on test of arcing ground suppressor

Territorial Limitation of the Operation of a Single Arc Suppressor. The best location of the arc suppressor is usually at the power house, although cases may arise where some central switching station gives greater convenience. To get figures on the limitation of a device, the line constants of a 45-kilovolt system are used as a basis. The Y potential to ground is normally 26 kilovolts the charging current about 0.15 amperes, per mile and the inductive reactance about 0.75 ohms per mile and impedance 0.86 ohms per mile at 60 cycles.

Assume one phase grounded at the power house by the operation of its protecting switch caused by an insulator arcing over far out on a straight away line. The potential of this phase at the generator is zero, but the line wire is not zero throughout its entire length. There may be a considerable potential at the faulty insulator. This is found by multiplying the total charging current in the line by half the impedance.

Since all the treatises on the subject of line capacity assume a normal condition of no grounded phase, the electrostatic capacity to the ground can be and is neglected. When a phase is grounded the several factors take on variable degrees of importance and become confused. On this account a discussion is here given of grounded phase capacities; first, in an analogy, second, in its physical theory, and third, in its mathematical theory.

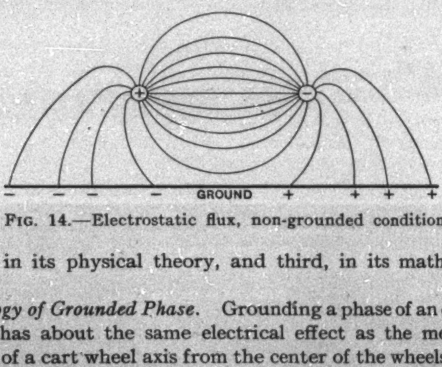

FIG. 14.—Electrostatic flux, non-grounded condition

Analogy of Grounded Phase. Grounding a phase of an electrical system has about the same electrical effect as the mechanical shifting of a cart wheel axis from the center of the wheels to some excentric point out near the rim of the wheels. The body of the cart would rise and fall by the amount of the excentricity. Theoretically, it would not require any more total energy to pull the cart because the energy given to lift the body is returned when it descends. At a high speed the cart would progress by jumps. In a three-phase electric circuit with one phase grounded all the apparatus will rise and fall in potential during every half-cycle. If there is resonance, the rise will be more than Y potential. If the ground is arcing, the electrical conditions correspond to a flat wheel on the cart. Every time it drops it bumps and sets up vibrations or oscillations throughout the body or system.

Physical Theory of a Grounded Phase. For simplification assume the condition of a single-phase circuit with the wires equally distant from ground. If the two wires are connected to a generator, one wire, at an instant, will be charged to a definite positive potential above earth potential and the other to an equal negative potential below earth potential. There will be two sets of static fluxes or displacement currents. One set passes between conductors without intervention. The other set passes between conductors with the intervention of the earth's surface. In terms of displacement, the earth being a conductor, collapses all the static lines that would have existed in that same volume. In so doing it shortens the path between conductors slightly and by releasing the static stress in that neighborhood, lines of static force from elsewhere in the static field will be pressed into the earth in order to balance all the forces. The conditions are shown in Fig. 14. According to the older method of representation there is both a negative and positive charge at zero potential induced on the earth.

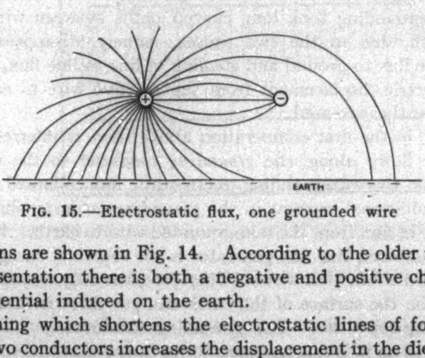

FIG. 15.—Electrostatic flux, one grounded wire

Anything which shortens the electrostatic lines of force between two conductors increases the displacement in the dielectric. The total displacement in the dielectric is the quantity of electricity in the electrostatic charge. Since the definition of the capacity is the ratio of the quantity of static electricity to the electric pressure, the capacity is increased by anything which shortens the static lines of force. When the earth is at a relatively great distance from the two line conductors it will not be in a dense part of the electrostatic field between conductors and will not, therefore, shorten appreciably any great percentage of the displacement flux. In other words, the presence of the earth will not much affect the electrostatic capacity of the wires.

If now the negative wire is connected to earth, all the electrostatic lines of force between that conductors and earth will be collapsed by the fact that the displacement in the dielectric is relieved by a conduction current through the vertical *grounding conductor*. Following along any line of force in Fig. 14 from positive wire to negative wire through the earth, any static line of force has been shortened by one-half. The conditions of dielectric displacement are represented in Fig. 15. There are several things that have taken place:

First, the electrostatic flux between the negative wire and the ground has disappeared.

Second, the electrostatic flux between the positive wire and the ground has expanded to fill up the space left free by the collapse of the flux between the negative wire and ground.

Third, the entire field of flux has been bent down toward the earth. The earth is now one terminal and by its great surface gives a relatively shorter distance for many lines which previous to the grounding took long curved paths between wires.

Fourth, due to the two causes, namely, disappearance of negative flux to ground and stealing of line to line flux, the flux or dielectric displacement from the positive wire to earth has been greatly increased.

Fifth, in the first enumeration above there is inferred that a current flows along the *grounding conductor* to the negative line when the corresponding electrostatic flux collapsed. There is an additional current in the *grounding conductor* due to the increase in flux from the non-grounded wire to earth. It should be remembered that the generator is the source of energy and is connected to the line wires. Therefore, the only way the single charge on the surface of the earth can get there is through the *grounding conductor*. The grounding conductor is not shown in Fig. 15 as it is not assumed to be in the plane of the paper.

Sixth, in the foregoing fifth enumeration it has been stated that the grounding offers a shorter path for some of the lines of force between wires by way of the earth. In other words, for the same potential difference between wires there is less displacement current to the grounded line wire—its electrostatic capacity is less. There is another significance to this statement. Some of the charging current to satisfy the capacity between wires which formerly flowed along the negative wire now flows to the earth through the grounding connection.

Seventh, the positive or non-grounded wire has a greater flux or displacement current for the same difference of potential between generator terminals and, therefore, its capacity is increased. In other words, it has a greater charging current after grounding the other line wire than before.

The conditions are shown diagrammatically in Fig. 16. The charging current to ground is A_2, to the negative wire is A_1 which is much below normal value, and the total capacity current to the non-grounded line wire is $A_1 + A_2$.

Summing up this physical theory, the grounding of a wire of a single-phase system does the following things in general:

1. It brings into prominence the capacity of the non-grounded wire relative to the earth. This capacity corresponds to the condition of a single overhead conductor with earth return.

2. Since this capacity is distributed and the grounding connection only at one point, the capacity current must flow along the wire to the earth connection during each half cycle of the generator.

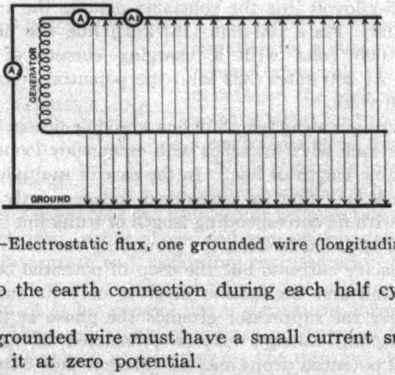

FIG. 16.—Electrostatic flux, one grounded wire (longitudinal view)

3. The grounded wire must have a small current supplied to it to keep it at zero potential.

The relative values of the foregoing factors must be determined by calculation.

With the solution of the value of current to ground in hand, the proof is easy of the initial statement that a grounded wire does not remain at zero or ground potential throughout its length. It may be added that its potential difference to ground varies directly as the distance away from the grounded point of the line. The charging current that flows into and out of the grounded phase wire in an endeavor to keep it at zero potential must pass through the inductance and resistance of the wire. Using the well known method of assuming the capacity of the total length of line concentrated at half the length, and using the charging current of this condenser passing through half the inductance of the line, the drop of potential from the protecting grounding switch to the faulty insulator assumes the following form:

$$e = \tfrac{1}{2}\, L\, w\, I_c$$

per mile, where L and I_c are the inductance and charging current per mile. Since the inductance and capacity current both have to be multiplied by the number of miles to the faulty insulator the equation for the potential becomes

$$e = \tfrac{1}{2}\, L\, w\, I_c \times (\text{miles})^2$$

For a 45-kilovolt line the constants assume the approximate value of 0.06. For a 100-mile (161-km.) line the drop should be about 600 volts with a charging current of about 15 amperes. At 200 miles (322 km.) the potential drop should be about 2400 volts.

Such a straight away length of line would be unusual but radial trunk lines each with branches with emergency loops may give a considerable length of line. In the case of multiple branches, each branch may first be considered independently, and then combined with its corresponding length of trunk line inductance. In the case of radial feeders, the grounding current is the sum of all the capacity currents but the drop of potential between the arcing ground and the station involves only its own capacity current after the suppressor grounds the phase at the station.

The foregoing voltages may be considered the usual values. The actual potential drops may be different due to three causes:

1. The apparatus has capacity.
2. An overhead grounded wire introduces a favorable element.
3. The instantaneous values of charging current during an arcing ground are many times as great as the 60-cycle charging current. Numerous oscillograms illustrating this condition were shown at the Frontenac meeting of the Institute by Mr. S. D. Sprong and the writer. The sudden current rushes when the arc is relighted at considerable potential produce a correspondingly higher drop of potential at the faulty insulator. There are still other factors which enter. Sufficient to say, however, that tests on the Southern Power Company's System, one of

the largest in the world, show that the length of line that can be protected by a single protector is ample to cover all existing systems.

Mathematical Solution of Capacities.—In the following mathematical solutions the fundamental equation for the potential of a conductor in electrostatic units is used as a starting point.

$$V_1 = 2\ Q_1 \log_e \frac{\text{distance between wires}}{\text{radius of wire}} \qquad (1)$$

where V_1 is the potential to earth or neutral and Q_1 the quantity of electricity per unit length.

$$V = 4\ Q \log_e \frac{\text{distance between wires}}{\text{radius of wire}} \qquad (2)$$

where V is the total potential. The former is necessarily the equation for a wire with ground return because all the potential is between the wire and neutral and the latter for two wires with a neutral between them.

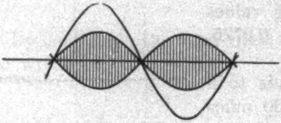

FIG. 17

Much confusion in writing potential equations will be avoided if it is initially noted that our usual linear representation of a sine wave of potential, rising above and successively falling below zero is an inaccurate and misleading representation of what is taking place in an alternating current circuit, although, it must be confessed, it is for general use a convenient form in which to use it. The oscillograms of voltage or potential (so called) repeat this inaccuracy and further fix the misconception. The bifilar oscillograph never gives a potential curve. It produces a current curve that is proportional to the difference of potential. This potential difference produces a current first in one direction then in the other, which gives the misrepresentation of the potential of the generator. For example, an oscillogram giving a positive peak potential of 140 volts indicates that when the potential reverses to the same negative value that the total change of potential is 280 volts. The actual maximum difference of potential either instantly or successively is only 140 volts. In Fig. 17 is shown the oscillogram in the large sine wave and the real potential waves in the twin curves which increase one positively and the other negatively simultaneously; each curve has a value of $\frac{1}{2} E \sin \alpha$. To bring equations (**1**) and (**2**) to practical units involves the value of the velocity of light. Slightly varying values have been used. In volts, coulombs, microfarads, and common logarithms the equation for potential of a mile length of two parallel overhead wires becomes:

$$V = \left(\frac{4}{.078} \log \frac{r_{12}}{r}\right) Q = \left(51.3 \log \frac{r_{12}}{r}\right) Q \qquad (\mathbf{3})$$

r_{12} is the distance from the center of one wire to the surface of the other, or with sufficient approximation from center to center of the aerial wires, Q is the number of coulombs per mile. The value 0.078 is the transformation constant depending on the velocity of light, logarithms, etc., mentioned above. From the authors the writer has immediately at hand, the following values are found: 0.0772, 0.0775, 0.0776, 0.0784 and 0.0845.

The constant 0.078 corresponds to a velocity of light of about 184,000 miles (29.6×10^9 cm.) per sec. The constant 0.0845 corresponds to a velocity of 179,000 mi. (28.8×10^9 cm.) per sec.

The assumption is made that the law of potential of a conductor due to its own charge and that of several charges around it is known. Then for the two conductors in Fig. 17*a* with the dimensions shown, positive charges on both conductors and the earth as a return.

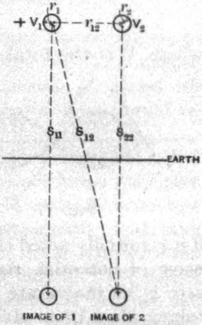

FIG. 17A

$$V_1 = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 + \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 \qquad (\mathbf{4})$$

$$V_2 = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 + \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 \qquad (\mathbf{5})$$

The factors in parenthesis are known as potential coefficients.

Starting with equations (**4**) and (**5**) a number of numerical problems will be solved all of which unless otherwise designated will have the following constants. Size of all wires the same, *viz.*, No. 0 B. & S., radius of wire, $r_1 = r_2 = 0.1624$ in. (4.07 mm.). Distance between centers, 48 in. (1.219 m.). Height above ground 360 in. (9.14 m.); therefore, $s_{11} = s_{22} = 720$ in. (18.28 m.). The diagonal distance S_{12} is about 722 in. (18.33 m.).

Problem 1. Find the capacity of wire 1 when wire 2 is used as return. For convenience an instant in time will be chosen when wire 1 is positive in every case following. Wire 1 is at $+V_1$ above zero potential and wire 2 is at $-V_2$ potential below the earth. The total potential difference is $V_1 + V_2 = V$. The generated potential is equally positive and negative and since the two wires are of the same size and parallel with the earth, they are in symmetrical relation and therefore $V_1 = -V_2$. The same argument holds in respect to the quantities of electricity, therefore $Q_1 = -Q_2$. Equation (**4**) then becomes

$$V = \left[51.3 \left(\log \frac{s_{11}}{r_1} - \log \frac{s_{12}}{r_{12}} \right) \right] Q_1 \qquad \textbf{(6)}$$

By combining the logarithms the total capacity of wire 1 may be written

$$C_1 = \frac{1}{51.3 \log \left(\dfrac{s_{11}}{s_{12}} \dfrac{r_{12}}{r_1} \right)} = \frac{1}{51.3 \left(\log \dfrac{s_{11}}{s_{12}} + \log \dfrac{r_{12}}{r_1} \right)} \qquad \textbf{(7)}$$

This equation for the capacity between conductors has an unfamiliar appearance due to the presence of $\log \frac{s_{11}}{s_{12}}$ which represents the effect of the ground in increasing the capacity of the conductors. The ratio of the height of a conductor above its image to the diagonal distance to the image of the other conductor is approximately one for all usual conditions of overhead wires. In this case the log of the ratio $\frac{720}{722}$ produces only 0.000003 microfarads difference in the capacity of a wire. The capacity of wire 1 cones to 0.0079 microfarads, or more conveniently expressed 7.9 milli-microfarads.

In order to learn when the presence of the ground might become a factor in the capacity worthy of consideration the two wires were separated to 150 in. (3.81 m.) and the height above the earth calculated such that an error of one per cent would be involved in the value of capacity when the presence of the earth is neglected. The height of the wires is 16 ft. (4.87 m.) It is evident that it would be necessary to string the wires on separate pole lines to make it worth while to use the complete equation.

The standard simplified equation of an overhead wire and return with no grounds on either is

$$C = \frac{1}{51.3 \log \frac{r_{12}}{r_1}} \text{ microfarads per mile.} \qquad \textbf{(8)}$$

Problem 2. What is the capacity of wire 1 when wire 2 is grounded? And under this condition what is the capacity of wire 2 and the earth? What is the distribution of charge between wire 2 and the earth? In equation (**4**) and (**5**) the following new conditions are introduced. The potential of wire 2 becomes zero, $-V_2 = 0$. The potential difference between the wires remaining constant, wire 1 rises to $V_1 + V_2 =$ say V. The charge Q_2 remains negative at zero potential.

$$V = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 - \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 \qquad \textbf{(9)}$$

$$O = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 - \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 \qquad \textbf{(10)}$$

With wire 1 connected to one terminal of the generator, and wire 2 and the earth to the other terminal, there are evidently three quantities of electricity to be considered, namely $+Q_1$ on wire 1 and an equal negative charge distributed between wire 2 (*i.e.*, Q_2) and the earth. The quantity of electricity on the earth is not represented in the equation directly, therefore, it must be found from $Q_1 - Q_2$. Equation (**10**) gives immediately the ratio of charge between wires 1 and 2 and, therefore, also the ratio of capacities C_1 to C_2.

$$Q_2 = \frac{\log \frac{s_{12}}{r_{12}}}{\log \frac{s_{22}}{r_2}} Q_1 \qquad \textbf{(11)}$$

Substituting equation (**11**) in equation (**9**) gives an expression from which the total capacity of wire 1 can be taken.

$$C_1 = \frac{1}{25.65 \log \frac{s_{11}}{r_1} - \frac{\left(25.65 \log \frac{s_{12}}{r_{12}}\right)^2}{25.65 \log \frac{s_{22}}{r_2}}} \qquad \textbf{(12)}$$

In the numerical example this gives 11.9 milli-microfarads per mile for wire 1. By grounding wire 2 the capacity of wire 1 has increased from 7.9 to 11.9 milli-microfarads which is 153 per cent.

The ratio of the quantity of electricity Q_2 on wire 2 to the quantity on wire 1 is

$$Q_2 = \frac{1.176}{3.647} Q_1 = .322\, Q_1 \qquad \textbf{(13)}$$

Since wire 1 contains the total quantity of electricity and wire 2 has 32 per cent of the opposite sign, the rest, namely 78 per cent, is on the earth.

The capacity of wire 2 has been reduced by being grounded. From equation (**13**) it can be found directly, or by substituting equation (**13**) in equation (**9**) again it can be expressed as follows:

$$C_2 = \frac{1}{\frac{\left(25.65 \log \frac{s_{11}}{r_1}\right)^2}{25.65 \log \frac{s_{12}}{r_{12}}} - 25.65 \log \frac{s_{12}}{r_{12}}} \qquad \textbf{(14)}$$

Numerically this becomes in the example 3.83 milli-microfarads.

The capacity of wire 2 drops, on grounding, from 7.9 to 3.83 which is to 48½ per cent. In other terms, wire 2 lost 52 per cent, which is just about the amount gained in capacity by wire 1 due to the grounding of wire 2.

Problem 3. One wire with earth return, the other wire being insulated. In this case the potential of wire 1 must be taken, as in the 2nd example, as twice the potential to neutral, that is $2\, V_1 = V$. The symbol for the potential of the insulated wire 2 remains V_2 as it now is. Since, however, it is insulated its charge Q_2 is zero. There will be a separation of equal charges of positive and negative electricity due to the electrostatic induction from wire 1 and the earth, or in other terms, some of the electrostatic flux from wire 1 will pass into and immediately out of the wire 2 in a general perpendicular direction. Since the path of the electrostatic flux is shortened by only the diameter of wire 2, the presence of wire 2, which is at some distance from wire 1, will have no appreciable effect on its value of electrostatic capacity. Equations (**4**) and (**5**) become:

$$V = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 \qquad (\mathbf{15})$$

$$V_2 = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 \qquad (\mathbf{16})$$

The capacity of wire 1 is

$$C_1 = \frac{1}{25.65 \log \frac{s_{11}}{r_1}} \qquad (\mathbf{17})$$

In the numerical example it becomes 10.64 milli-microfarads. This capacity of a single wire with ground return is 135 per cent of that of a wire when two wires with no grounding exists, and 89½ per cent of its value when wire 2 is grounded.

Since wire 2 has no charge its capacity is useless. Its potential may be found by substituting the value of Q_1 of equation (**15**) in equation (**16**).

$$V_2 = \frac{\log \frac{s_{12}}{r_{12}}}{\log \frac{s_{11}}{r_1}} V \qquad (\mathbf{18})$$

Numerically, this gives $V_1 = 0.322\ V$, the fraction 0.322 is the value of the mutual capacity of wires 1 and 2 previously determined.

Problem 3*a*. Distance between two non-grounded wires to give the same capacity as one wire with earth return. It has been demonstrated that one No. 0 B. & S. wire with earth return at 30 ft. (9.14 m.) distance gives a greater capacity than a return wire at 48 in. (1.21 m.). The ratio is 10.64 to 7.9. How close will these two non-grounded wires have to be placed to give 10.64 milli-microfarads? The answer is 10.82 inches (25.72 cm.)

Problem 4. When two overhead wires are connected to potentials of the same sign and a ground return is used, the conditions are similar to those that Heaviside solved for telegraph circuits some thirty years ago.

Assume the conductors are of the same diameter and connected to the same bus bar. This corresponds in practice to the condition of two wires of the same phase but of a different circuit on the same pole line.

Then $+V_2 = +V_1$, and Q_2, no matter what its value, is equal to Q_1 so long as the two wires are at the same height above ground and have similar environments, Q_1 and Q_2 are both positive.

The equations of the potentials take the following forms:

$$V_1 = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 + \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 \qquad (19)$$

$$V_2 = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 + \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 \qquad (20)$$

The capacity of either wire 1 or wire 2 is:

$$C_1 = C_2 = \frac{1}{25.65 \left(\log \frac{s_{11}}{r_1} + \log \frac{s_{12}}{r_{12}}\right)} = \frac{1}{25.65 \log \frac{s_{11}\, s_{12}}{r_1\, r_{12}}} \qquad (21)$$

The corresponding numerical solution for the factors chosen previously, gives the value of 8.1 milli-microfarads for each wire to ground. Since the two wires are at the same potential their mutual capacity is useless.

When wire 1 alone was used it gave 10.64 milli-microfarads to ground but when 1 and 2 are used together wire 1 gives only 8.1 milli-microfarads (76 per cent) to ground. Wire 2 has the same capacity to ground, and since the two wires now form parallel condensers the total capacity to ground is 16.2 milli-microfarads. It should be noted that the two wires in parallel give a greater capacity than one wire but not twice as great. The ratio for two No. 0 wires spaced 48 in. (1.21 m.), 30 ft. (9.14 m.) above ground, is 153½ per cent increase in capacity over one wire. In other words, one of these wires is in the electrostatic field of the other and can not therefore add its full displacement flux.

If the two wires were on separate pole lines then one would be well out of the region of dense flux of the other and the capacities of the two together toward earth would, therefore, be more nearly equal to twice the capacity of one toward earth. As an example, take a spacing of 100 ft. or 1200 in. (30.48 m.) between lines instead of 48 in. (1.21 m.). This gives a capacity for each wire toward ground as 10.52 milli-microfarads.

The two wires as parallel condensers give twice 10.52 milli-microfarads equal 21.04 milli-microfarads which is about 1.98 (nearly twice) the capacity of one alone toward ground.

Problem 5. The capacity of wire 1 to wire 2 is indeterminate in this foregoing case. It becomes determinate if wire 1 and wire 2 are not connected together and are charged to a different positive potential. This condition corresponds to a telegraphic circuit, a problem that Mr. Oliver Heaviside included in his general solution. This solution is reproduced here in terms of practical units, to bring out the relations of " capacity coefficients " and " mutual capacity coefficients."

It will prevent confusion if it is emphasized now that the " capacity coefficient " is not the capacity except where the " mutual capacity coefficient " is associated with a charge at zero potential.

Equations (**4**) and (**5**) can be simplified for purposes of convenience by the use of " potential coefficients " as follows:

$$V_1 = p_{11} Q_1 + p_{12} Q_2 \tag{22}$$

$$V_2 = p_{12} Q_1 + p_{22} Q_2 \tag{23}$$

The solution of these equations in terms of quantity give

$$Q_1 = \frac{p_{22}}{p_{11} p_{22} - p_{12}^2} V_1 - \frac{p_{12}}{p_{11} p_{22} - p_{12}^2} V_2 \tag{24}$$

$$Q_2 = - \frac{p_{12}}{p_{11} p_{22} - p_{12}^2} V_1 + \frac{p_{11}}{p_{11} p_{22} - p_{12}^2} V_2 \tag{25}$$

In terms of "capacity coefficients" and "mutual capacity coefficients" they take the convenient form

$$Q_1 = C_{11} V_1 - C_{12} V_2 \tag{26}$$

$$Q_2 = - C_{21} V_1 + C_{22} V_2 \tag{27}$$

Where C_{11} is the "capacity coefficient" of wire 1 and expressed in terms of dimensions is

$$C_{11} = \frac{25.65 \log \frac{s_{22}}{r_2}}{Z} \tag{28}$$

Z is the denominator common to all the coefficients, namely, C_{11}, C_{12}, C_{21}, and C_{22}. It has a value

$$Z = \left(25.65 \log \frac{s_{11}}{r_1}\right) \left(25.65 \log \frac{s_{22}}{r_2}\right) - \left(25.65 \log \frac{s_{12}}{r_{12}}\right)^2 \tag{29}$$

The "mutual capacity" between conductors $- C_{12}$ is equal to $- C_{21}$

$$- C_{12} = \frac{25.65 \log \frac{s_{12}}{r_{12}}}{Z} \tag{30}$$

and the "capacity coefficient" of wire 2 is

$$C_{22} = \frac{25.65 \log \frac{s_{12}}{r_1}}{Z} \tag{31}$$

If the wires are the same size and the same height above ground then their "capacities coefficients" are identical $C_{11} = C_{22}$ and are identical with the values already calculated by the potential equations.

The "mutual capacity coefficient" for the numerical problem is 3.83 milli-microfarads per mile. It is the same value as found for the capacity of wire 2 toward wire 1 when wire 2 was grounded. But it is entirely different from the capacity of wires 1 to 2 when neither is grounded. The coefficient of "mutual capacity" is always negative. Let us examine what this means. Gradually change V_2 and follow the effect produced.

In equation (**26**) the quantity of electricity Q_1 on wire 1 is diminished in proportion to the "mutual capacity" C_{12} if the potential of wire 2 is of the same sign as V_1. An example has already been worked out, namely when the two wires were connected together *i.e.*, $V_2 = V_1$. At a distance of 48 in. (1.21 m.) apart, wire 1 had a capacity of 8.1 milli-microfarads toward earth whereas when wire 2 was grounded wire 1 had a capacity of 11.9 milli-microfarads total. In other words, the quantity of electricity on wire 1 was diminished by the proportion $11.9 - 8.1 = 3.8$ milli-microfarads due to the "mutual capacity coefficient" and making the potential of $V_2 = V_1$. At this potential both wires are charged, say, positively. Now imagine wire 1 and 2 disconnected and the potential of V_2 gradually diminished by changing the potential of the source. As this process takes place Q_1 increases because the subtraction effect of the "Mutual capacity coefficient" in equation (**26**) is decreasing. At the same time the quantity of electricity on wire 2 is diminishing. This charge will reach zero before the potential V_2 equals zero. It will in fact take place when $C_{22}\,V_2 = C_{12}\,V_1$

$$V_2 = \frac{C_{12}}{C_{22}}\,V_1 = \frac{3.8}{11.9}\,V_1 = 0.32\,V_1$$

As V_2 decreases still further toward zero the quantity on wire 2, namely Q_2, changes sign and becomes negative. When V_2 reaches zero then the subtraction factor involving the "coefficient" of mutual capacity in equation (**26**) disappears.

If now the potential V_2 of wire 2 is made negative then the factor containing the "mutual capacity coefficient" in equation (**26**) becomes positive and a still further quantity is now added to wire 1 by the "mutual capacity". The quantity on wire 2, already turned negative, continues to increase in negative value with the change of potential.

From this cycle of change it is seen that the total capacity may be the sum or difference of the "capacity and mutual capacity coefficients," or it may be equal to the "capacity coefficient" itself according to the sign and value of the potential associated with the coefficient of "mutual capacity." There is less possibility of an error in signs if the total capacity is solved directly from the equations of potential coefficients as used by the writer.

Problem 6. Effect of overhead grounded wire. These single-phase relations can be extended to three-phase, but before involving the third wire in the circuit, it is important in connection with protection against accidental arcing grounds to note the effect of an overhead grounded wire under two conditions, namely, normal operation and one phase grounded. If the grounded overhead wire were placed at the symmetrical neutral plane it would have no effect on the capacity currents during normal operation. Fig. 17*b* shows the condition chosen. Wire 3 is an overhead grounded wire and wire 2 is grounded.

$$V = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 - \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 - \left(25.65 \log \frac{s_{13}}{r_{13}}\right) Q_3 \tag{32}$$

$$O = \left(25.65 \log \frac{s_{21}}{r_{21}}\right) Q_1 - \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 - \left(25.65 \log \frac{s_{23}}{r_{23}}\right) Q_3 \tag{33}$$

$$O = \left(25.65 \log \frac{s_{31}}{r_{31}}\right) Q_1 - \left(25.65 \log \frac{s_{32}}{r_{32}}\right) Q_2 - \left(25.65 \log \frac{s_{33}}{r_3}\right) Q_3 \tag{34}$$

$$V = p_{11} Q_1 - p_{12} Q_2 - p_{13} Q_3 \tag{35}$$

$$O = p_{12} Q_1 - p_{22} Q_2 - p_{23} Q_3 \tag{36}$$

$$O = p_{13} Q_1 - p_{23} Q_2 - p_{33} Q_3 \tag{37}$$

The solution of equations (**35**),(**36**) and (**37**) gives

$$V = \left[p_{11} - \frac{p_{12}^2}{p_{22}} + \frac{p_{12}\, p_{23}}{p_{22}} \left(\frac{p_{13}\, p_{22} - p_{12}\, p_{23}}{p_{33}\, p_{22} - p_{23}^2} \right) - p_{13} \left(\frac{p_{13}\, p_{22} - p_{12}\, p_{23}}{p_{33}\, p_{22} - p_{23}^2} \right) \right] Q_1 \tag{38}$$

This equation will give the value of capacity for wire 1 but since we desire not hair splitting refinements but just the general effect, a very approximate solution can be obtained easier by certain assumptions.

Approximately:

$$p_{11} = p_{22} = p_{33} \tag{39}$$

$$p_{12} = p_{23} = p_{13} \tag{40}$$

Substituting these values,

$$V=\left[p_{11}-\frac{p_{12}^2}{p_{11}}+\frac{p_{12}^2}{p_{11}}\left(\frac{p_{12}\,p_{11}-p_{12}^2}{p_{11}^2-p_{12}^2}\right)-p_{12}\left(\frac{p_{12}\,p_{11}-p_{12}^2}{p_{11}^2-p_{12}^2}\right)\right]Q_1 \qquad \textbf{(41)}$$

$$p_{11}=25.65\log\frac{720}{0.1624}=94.6 \qquad \textbf{(42)}$$

$$p_{12}=25.65\log\frac{720}{48}=30.16 \qquad \textbf{(43)}$$

$$V=80\,Q_1$$
$$C_1=0.0125$$

With wire 2 only grounded the capacity of wire 1 was 11.9 milli-microfarads. Therefore the increase due to the presence of the ground wire is 0.6 milli-microfarads, an increase of only 5 per cent.

A more important question to answer is, how much does the overhead grounded wire relieve wire 2 of the electrostatic charging current. Since wires 2 and 3 are equidistant from wire 1, $Q_2=Q_3$ approximately, and the ratio $\frac{Q_2+Q_3}{-Q_1}$ is the relative capacity of wires 2 and 3.

From equation (**34**) of the group,

$$p_{23}\,Q_2+p_{33}\,Q_3=p_{13}\,Q_1 \qquad \textbf{(44)}$$

$$Q_2=\left(\frac{p_{13}}{p_{23}+p_{33}}\right)Q_1=\left(\frac{30.16}{30.16+94.6}\right)Q_1 \qquad \textbf{(45)}$$

$Q_2=25.2$ per cent Q_1 $\qquad C_2=0.00315$
$Q_3=25.2$ per cent Q_1
Q (on ground) $=48.6$ per cent Q_1

Total—100 per cent

The presence of the grounded overhead wire has reduced the charging current on wire 2, when it is grounded, from 32.2 to 25.2 per cent that is, to 78½ per cent of its previous value or ¼ of its normal value. Thus the overhead grounded wire increases the range of distance over which a single arcing ground surpressor will protect.

Problem 7. Capacity of wire 1 entirely surrounded.

It is of some interest to figure out the ultimate upper limit of capacity of wire 1 when surrounded by numerous wires grounded and spaced 48 in. (1.21 m.) from wire 1. This is easily done by assuming that the grounded wires form practically a solid tube around wire 1. Then the formula becomes that for a concentric cable.

$$C = \frac{1}{25.65 \log \dfrac{48}{0.1624}} = \frac{1}{63.4} = .0158 \text{ microfarads per mi.} \quad \textbf{(46)}$$

It is seen at a glance at the equation that the capacity of the concentric condition is just twice the capacity (100 per cent increase) of two wires of the same metallic spacing not grounded. The addition of the first few wires distributed on a circumference of 48-in. (1.21-m.) radius rapidly raises the capacity of wire 1 toward its ultimate maximum. Each of the surrounding wires has its capacity lowered by subdivision of the charge.

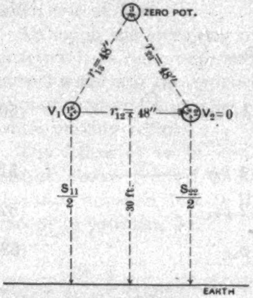

FIG. 17B

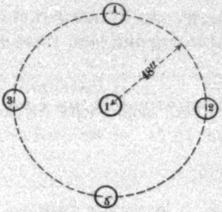

FIG. 17C

By dividing the circumference of a 48-in. (1.21-m.) radius into 1870 wires set close together each wire would have a proportional part of the capacity of the central wire giving each a capacity of about 8½ micro-microfarads.

Problem 8. Wire 1 surrounded by four wires symmetrically placed, but not grounded. To give a numerical conception of the foregoing statement and also to show short methods in calculations the problem of Fig. 17*c* is solved:

If wires 2, 3, 4 and 5 are connected together but not grounded what are the capacities? The two equations involving the "potential coefficients" may be written directly:

$$V_1 = p_{11}\,Q_1 - p_{12}\frac{Q_1}{4} - p_{13}\frac{Q_1}{4} - p_{14}\frac{Q_1}{4} - p_{15}\frac{Q_1}{4} \qquad (47)$$

$$-V_1 = p_{12}\,Q_1 - p_{22}\frac{Q_1}{4} - p_{23}\frac{Q_1}{4} - p_{24}\frac{Q_1}{4} - p_{25}\frac{Q_1}{4} \qquad (48)$$

$$\text{Total } V = (p_{11} - p_{12})\,Q_1 - (p_{12} - p_{22})\frac{Q_1}{4} - (p_{13} - p_{23})\frac{Q_1}{4}$$

$$- (p_{14} - p_{24})\frac{Q_1}{4} - (p_{15} - p_{25})\frac{Q_1}{4} \qquad (49)$$

$$V = (p_{11} - p_{12})\,Q_1 + (p_{22} + p_{23} + p_{24} + p_{25})\frac{Q_1}{4}$$

$$-(p_{12} + p_{13} + p_{14} + p_{15})\frac{Q_1}{4} \qquad (50)$$

Approximately $p_{12} + p_{13} + p_{14} + p_{15} = 4\,p_{12}$ (51)

$$p_{24} + p_{25} = 2\,p_{24} \qquad (52)$$

$$p_{11} = p_{22} \qquad (53)$$

Collecting these terms:

$$V = \left(1.25\,p_{11} + \frac{p_{23}}{4} + \frac{p_{24}}{2} - 2\,p_{12}\right) Q_1 \qquad (54)$$

Approximately the numerical values become:

$$p_{11} = 25.65 \log \frac{720}{0.1624} = 25.65 \times 3.646 = 93.5 \qquad (55)$$

$$p_{23} = 25.65 \log \frac{720}{96} = 25.65 \times 0.875 = 22.4 \qquad (56)$$

$$p_{24} = 25.65 \log \frac{720}{67.8} = 25.65 \times 1.025 = 26.3 \qquad (57)$$

$$p_{12}=25.65 \log \frac{720}{48}=25.65\times 1.176=30.15 \tag{58}$$

$$V=(1.665+5.6+13.15-60_1 3)\,Q_1 \tag{59}$$

$$C_1=\frac{1}{75}=0.01354 \text{ microfarads per mi.} \tag{60}$$

The four wires surrounding wire 1 increase its capacity $\frac{13.54}{7.9}=172$ per cent.

Wire 2 of surrounding wires has its capacity reduced from 7.9 milli-microfarads, when alone, to $\frac{13.54}{4}=3.38$ milli-microfarads when one of four.

Although the foregoing problem is not one likely to be met in practice it is only necessary to ground the surrounding or adjacent wires and the practical condition is reached of one circuit in operation and a parallel circuit on the same pole line grounded while making repairs.

The following table summarizes the numerical results. The height above ground is 30 ft. (9.14 m.) in every case and the distance between No. 0 B. & S. conductors 48 in. (1.21 m.) except in problem 3*a*.

Example	Dist. between wires	Condition	Comparable capacities milli-microfarads				$\frac{Q_2}{Q_1}$	$\frac{Q_g}{Q_1}$
1	48 in.	1 *vs.* 2 neither grounded	1 to 2 7.90	2 to 1 7.9	1 to gr. 0.003	2 to gr. 0.003	1	0
2	"	1 *vs.* 2 and G	1 to 2+G 11.90	2 to 1 3.83	1 to gr. 8.07	—	0.322	0.678
3	"	1 only *vs.* G	1 to G 10.64	—	—	—	0	1
3*a*	10.82 in.	1 *vs.* 2 neither grounded	1 to 2 10.64	2 to 1 10.64	—	—	1	0
4	48 in.	1 and 2 together *vs.* ground	1 to G 8.1	1+2 to G 16.2	—	2 to G 8.1	1	2
6	"	1 *vs.* 2+G+ gr. wire	1 to all 12.5	1 to 2 3.15	1 to gr. 6.2		0.25	0.50
7	48 in.	1 *vs.* cyl.	1 to cyl. 15.8	2 to 1 0.008			0.003	—
8	"	1 *vs.* 4 wires no G	1 to all 13.54	1 to 2 3.38			0.25	—

Having gone thus far with nothing but simple problems in sight, the writer doubts the advisability of taking up more space with further calculations. Numerical examples have shown general relations which can be extended to multiple conductors. High accuracy in capacity measurements of transmission lines is quite unnecessary and inconsistent in the light of errors introduced from such causes as harmonics, therefore in solving involved problems it is permissible to assume identities between the logarithms of ratios that are nearly alike. This simplifies complicated relations to such an extent that calculations are readily made. Certain other factors may be eliminated on inspection. For example, a parallel wire with practically zero charge disappears immediately from the equation of capacity of any other conductor. The earth at a total charge of zero affects inappreciably the capacity of a pair of conductors unless the earth forms an appreciable part of the total path of the electrostatic flux; in other words the earth at zero charge total exerts an inappreciable effect unless the two wires are nearer the earth than to each other. The earth when charged, *i.e.*, used as a return conductor, exerts a great influence on the capacity by its large surface. The mutual capacity between the conductor and one other of a surrounding group of wires can be estimated frequently by using a mean logarithmic distance and the concentric cable capacity of the conductor reduced with judgment to correspond to the surrounding condition.

So long as circuits operate normally with their natural neutral undisturbed the capacity and the mutual capacity relations have little vital interest but when an accidental arcing ground occurs these constants may rise suddenly to importance.

One of the important factors in contemplated protective dedevices is this one of mutual interaction of conductors.

Maintenance of the Accidental Arc at the Insulator. There are no data on the relations of voltage, current and arc length for accidental arcs on insulators. The dangers to insulation on a system in making such tests practically, are so great that operating engineers can not undertake the risk for the personal value of the results. The principal value of the results lies in their use to design an insulator which will extinguish its own grounding current. Such a thing is practicable on short lines. The solution of the problem of the relations of arc length to voltage, length of line, etc., involves a discussion of a number of factors relative to internal surges. The matter of internal surges is too extensive and too involved to find a place as part of this paper. Certain relations of arc current and potential, however, may be pointed out. Oscillographic studies have been made by a number of scientists on arcs for illuminating purposes. These arcs are maintained under stable conditions. Stable conditions involve arcs of comparatively short lengths in inductive circuits where the current lags more or less behind the impressed e.m.f. In a circuit where the capacity predominates the arc current reduces to zero before the potential and is not reëstablished in the opposite direction until the potential passes through zero and rises sufficient to reëstablish the arc. This interval between the extinction and relighting of the arc gives it a chance to cool and deionize. The potential to strike the arc across this space is frequently the spark potential of the gap. In other words, in order to maintain an arc in a condenser circuit, the arc length is frequently limited to the spark length. Furthermore, the arc is usually unstable even during a half cycle, when the potential is in one direction. As the voltage rises there is a spark, a sudden rush of current attended with more or less oscillations, and, since the condenser becomes charged, an extinction of the arc. This may be repeated any number of times during a half cycle of the generator, according to the local conditions.

If the grounding current of a line were purely capacity current most of the arcing grounds would be extinguished by the natural conditions. The inductance of the line and, since the same current as the current to ground must pass to the not-grounded phases through the coils of the generator and transformers, the inductance of the apparatus is involved. The presence of this inductance aids in maintaining a grounding arc although it is insufficient to produce a lagging current.

Some accidental flashes over single insulators are extinguished without causing a noticeable disturbance. These transient grounds have been noted and recorded on a lightning arrester discharge recorder but not actually observed.

From our knowledge of the conditions two possible explanations of the extinction of the arc may be made. First, the spark around the insulator may take place at an instant when the generator voltage is either decreasing or near zero. Second, the spark may take place on the lea side of an insulator and a favorable wind at right angles to the line whip out the arc.

When all these factors favorable to the extinguishment of the grounding arc are considered and there is added to this a metallic ground at the protector which maintains the generator end of the phase at constant zero potential and is in parallel with the arc with the intervention only of the line inductance, there is little or no chance of maintaining an arcing ground even at great distances from the protector.

Tests of Arc Lengths, Current, and Potential at Variable Power Factors. Long arcs by reason of their temperature tend to rise. They are wafted about by local air currents and frequently loop back and short circuit a part of the arc length. Some times an arc is entirely broken by a local air current and reëstablished by a spark in the succeeding half-cycle of the generator wave. These variations make it impossible to study an arc by means of the usual ammeters and voltmeters. By a combination of the oscillograph, photographic plates and revolving discs it is practicable to obtain instantaneous records which can be examined and measured at leisure. Some of the preliminary studies of long arcs are given herewith. These complicated tests were carried out by Mr. H. E. Nichols. A camera was placed behind a revolving disc which contained a hole to give successive exposures. A contacting device connected in circuit with one of the oscillographic vibrators makes the vibrator deflect every time an exposure of the camera is made. The arc length can be measured on the photograph and the simultaneous current and voltage at each exposure can be taken from the oscillogram since the other two vibrators were used to record the curves of current

This illustration shows six exposures. Each exposure had a duration of one milli-second. The time between exposures was eight cycles (0.13 sec.). The first exposure took place, as shown in Fig. 18*b*, four cycles after the current started. The arc was started by means of small wires projecting from each horn and, as the photograph plainly shows, the arc had not yet burned the fuse wire back to the horns. The third exposure shows the arc in the act of short circuiting a small upper loop. While this shortening took place at the highest part of the arc the other parts were being lengthened so that it happened that no appreciable change took place in the potential wave.

FIG. 18A

and voltage of the arc. It is then necessary to start the exposure on the oscillographic film and immediately afterwards the arc at the horns. Sometimes the arc was started by means of a static spark properly timed and at other times by means of a shortened gap. This latter consists in nearly closing the gap by means of a fine wire (3 mil. diameter in these tests). It is better thus to bridge only a part of the gap, rather than all of it with a fuse, as the arc will burn the fuse wire out of the way quicker than it can otherwise melt and blow it. This is important where small currents are involved and rapid action necessary.

A complete test consists of three parts, at least—namely, the photograph of the successive positions of the arc, the corresponding oscillogram, and the tabulated values or curves of arc length, versus potential or current. Since the study is being made with alternating currents there is some question concerning the proper expression for the voltage and current. Shall it be the effective value, the initial maximum, the usual value after the arc is established, or one of the several other expressions? The initial peak value of potential across the arc is important because it determines whether the arc can be relighted or not by the circuit. The more time the arc has to cool between half cycles of the generator wave the more the potential required to again establish the arc with the current in the opposite direction. In all these arcs there is usually a period about midway in the half-cycle when the current and potential hold briefly at nearly a constant value. These readings are valuable in giving information of the conditions of an established arc. The peak potential

FIG. 18B

The lower record shows the instant of exposure of the photographs of arcs, the middle record the current in the arc, and the upper record the potential across the arc. The transformer feeds a condenser and, therefore, the current leads the e.m.f. by 90 deg. The final values of current show that the arc ceases very gradually. The arc lengthens and cools, takes more voltage and decreases the current without any abrupt changes.

and the usual potential or potential of the established arc are plotted in the tests herewith reproduced.

Test No. 1. This test consists of four parts, Figs. 18*a*, 18*b*, 18*c*, 18*d*, *viz.*, photograph of the arcs on the horns, one oscillogram corresponding thereto, one oscillogram taken subsequently with the film at higher speed to show the detailed forms of waves of current and potential, and curves of arc length versus potentials and current. Comments and further details are given under each figure.

Test No. 2. Figs. 18*e*, 18*f*, 18*g* and 18*h*. This test differs from the previous test in that the circuit has high inductance and consequently a large angle of lag, of current behind the impressed e.m.f. The e.m.f. across the arc is in phase with the current. The wave shape of current is different and the e.m.f. across the arc correspondingly changed.

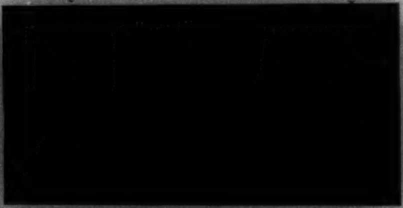

FIG. 18c

The current and potential of an arc in series with the same condenser. The last three cycles of potential show the normal form of potential across the arc. The first and second cycle are distorted by the effect of an air current on the arc which nearly extinguished it. In the second cycle the potential remained high for a proportionately long time before the current could get above 0.2 amperes. Apparently this particular arc had an unstable value at 0.2 amperes. Compare it to the stable condition of current shown in the succeeding cycles. After the third exposure there is evidence in the potential wave that the arc resistance decreased due probably to shortening. The position of the arc relative to the plane of the horns is not shown in the illustration (18*a*) and, therefore, the arc length is of somewhat indefinite value.

GENERAL DISCUSSION OF THE PROTECTIVE PROBLEMS

With the assurance that the new apparatus for the protection against an accidental grounded phase will do away with a large percentage of line troubles due to lightning, it seems worth while to make a general survey to determine the nature of the phenomena to be met and the degree of solution already achieved in the vital problem of absolute continuity of service.

Two New Terms to Express Conditions of Protection. In the discussion of phenomena relating to line protection, it has been necessary to coin terms to briefly express what would otherwise require a sentence or paragraph. Two of these terms are tentatively offered as follows:

Super-Spark Potential. Dielectric spark lag is a condition that has been known for several years. There is always this interval after potential is applied before the spark forms. During this period ionization of the gap takes place. If the applied potential is just equal to the spark potential it requires a considerable interval of time to ionize the gap. In one particular case described at the Jefferson meeting it required several seconds. As the applied potential is increased above the long-time-applied-spark potential the spark lag decreases. This potential in excess of the spark potential is herein designated as the super-spark-potential. So far as measured, the relation between the super-spark-potential and the dielectric-spark-lag is hyperbolic. As a numerical illustration, when the super-spark-potential was 10 per cent above the spark potential, the dielectric spark lag was 200 milliseconds. When it was 100 per cent above the spark potential, *i.e.*, double potential, the spark lag was reduced to five milliseconds.

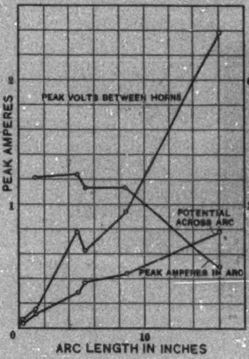

FIG. 18D

Curves of arc length versus current and potentials. Up to 10 in. the current preserves a nearly constant value of 1.2 amperes and then drops. Both the peak potential and the potential of the stable arc are nearly proportional to the arc length.

Dielectric-spark-lag should be distinguished from the lag in the formation of an arc around an insulator (or other device that involves corona streamers) when a spark potential at a normal frequency is applied. This distinction is made farther on.

The second new term that is used herein is bolt-peak, or sometimes, bolt-point.

Bolt-Peak. An overhanging thundercloud induces static electricity on the line which is graded in density according to the nearness of the point on the line to the charge in the cloud. The point of maximum charge is designated as the bolt-peak. When the bolt of lightning discharges to ground near the line, the bolt-peak on the line exists at a point having the shortest perpendicular distance to the path of the lightning. If the path of the lightning is inclined to the line the bolt-peak on the line may not be the point on the line nearest the point on the earth struck by the lightning bolt, although it usually is. If the line itself is struck the bolt-peak naturally occurs at that point.

Seven exposures of arc rising on horns. Exposure four shows a loop of arc short circuiting on itself at the highest point. Due to an accidental air current the arc rose better on one horn than on the other.

At the right is shown the arcs in the plane of the horns. This is taken by the use of a mirror at a 45-deg. angle to the camera. The photograph shows that the arcs are practically in the same place and measurements of the lengths on the front view side will be correct.

FIG. 18E

Nature of Surges on Overhead Lines. Separating the internal surges in apparatus from the surges in the line, it is convenient to treat line surges under three heads, namely, *lightning*, *resonance*, and *stationary waves*. The most frequent cause of trouble is lightning which is the subject of the following treatment.

Lightning Induction. Electrostatic induction on a transmission line is of a fairly uniform nature, although the induction differs in intensity from a negligible value up to a direct stroke coming from a large cloud or group of clouds. Not from actual observation, but from our knowledge of electrostatics, the following well known theory of the mechanism of charge and discharge has been formulated.

A charged cloud or its equivalent is in a position above the line. By electrostatic induction a charge is drawn onto the line because the line is nearer the cloud than the ground is. Assuming the case of a cloud nearly overhead and discharging to ground near but not onto the lines, the fixed charge on the lines at the moment of cloud discharge will be very much concentrated. Soon after it is freed it tends to spread over the lines and distribute itself uniformly. There is the corresponding charge of

FIG. 18F

This oscillogram of current and potential of the arcs is very similar to the previous case. The current starts higher, at 3.86 amperes, and gradually decreases—this, however, results from the regulation of the circuit.

A very important phenomenon in the theory of long arcs is illustrated during the last cycle of current. In the cycle before the last the potential rises to 12,500 volts and the current to 1.1 amperes. This half cycle wave of voltage shows the characteristic form for the potential drop across an arc but the following half-cycle does not, although there is a current in the arc. The voltage rises to 15,900 volts but it causes only a small current which has the nature of a leakage current. This current is insufficient to give the arc its usual "negative characteristics" and yet enough to prevent the gases from being entirely deionized.

During this brief period the photographic record does not show what changes are taking place in the arc length. However, some important information of the arc in its last flickers may be obtained from a tabulation of currents and potentials of the oscillogram. Starting with the first cycle after the extinction of the arc and working backward, in successive half-cycles, the difference of potential is 1,700 volts at zero current, 15,900 volts at 0.22 amperes, 12,500 volts at 1.1 amperes, 10,300 volts at 1.6 amperes, and 10,000 at 1.7 amperes. Up to the value of 2 amperes, the equation of these points follows a straight line

$$V = 17{,}000 - 8{,}210\,I$$

The equation cannot possibly hold true much beyond the limit given.

It is probable that during these last two cycles of current the arc does not change much in length. On this assumption that the potential of the dying arc varies directly with the product of current times resistance the resistance per unit length of the arc may be found. Using simultaneous values the potential was about 4,500 volts when the current was 1.1 amperes. This gives a resistance of 4,100 ohms total (180 ohms per inch, 2,160 ohms per ft., 71 ohms per cm.). At the peak value of 12,500 volts on the same half-cycle the simultaneous current was 0.15 amperes which gives a resistance of 83,000 ohms total (3,600 ohms per inch, 43,200 ohms per ft., 1,430 ohms per cm.). Calculations from the last half cycle of current at 0.22 amperes gives 73,000 ohms total (3,200 ohms per inch, 38,400 per ft., 1,250 ohms per cm.)

A useful value of resistance may be found by using the peak potential and peak current in each half cycle. These values are not simultaneous but they give an average resistance during a half cycle. The corresponding values are as follows: 12,500 volts, 1.1 amperes and 11,400 ohms total; 10,300 volts 1.6 amperes, and 6,400 ohms total; 10,000 volts, 1.7 amperes, and 5,900 ohms total. These tests, as already stated are preliminary and due to the methods of tests are only roughly approximate.

the opposite sign on the ground underneath. In order to move a charge of electricity, current, involving electromagnetic energy, must be built up; in other words the moving charge meets the self-induction of the line wire. Therefore the localized potential

FIG. 18G

Subsequent high speed oscillogram of arc rising on horns. Details of the shapes of the waves are evident. The same phenomenon of final current is again reproduced as in Fig. 18*f*. This current has a value of 0.09 amperes at 16,000 volts. The length of arc was not photographed but it is presumably about the same as the one photographed in Fig. 18*f*, *viz.*, about 23 in. (58.3 cm.) long.

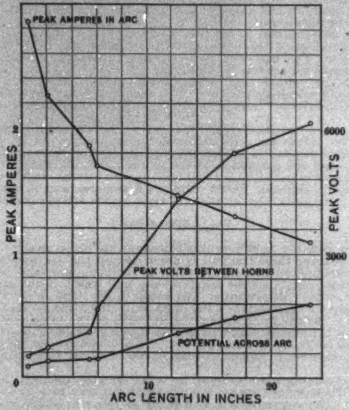

FIG. 18H

Arc length versus current and difference of potential. Since all three factors ,*viz.*, length, current and potential varied, it is not possible to deduce the equation for long arcs from it. However, it gives the exact phenomena taking place in horn gaps in series circuit.

will be held momentarily on the insulators. This much of the theory has been repeated a number of times.

Rapid Electrostatic Induction Causing Heavy Currents on the Line During Cloud Discharge. In addition to the foregoing there is a phenomenon taking place during vertical strokes not yet emphasized. At the instant that the charge is set free on the line there is reason to state that the charge is not in a quiescent condition.

Figs. 19 and 20 are attempts to illustrate what the theory leads us to believe takes place. Fig. 19 illustrates the quiescent condition. Fig. 20 is the active condition. While the bolt of ightning is forming, the rush of static from opposite directions magnifies the potential at the bolt-point on the line. Furthermore, the time of application of high potential is increased, due to the necessity of doubly transforming the electromagnetic energy of the current in order to reverse it in direction, and by its outward flow from the bolt-point relieve the strain. If the potential is high enough and the time of application long enough, a " spill-over " on the insulator about the bolt point will take place. If the bolt from the cloud strikes near the line the bolt-peak may send out a streamer to the main bolt, which is, in effect, a side-stroke to the line. This theory is given to lead up to a discussion of the use of arresters to protect lines.

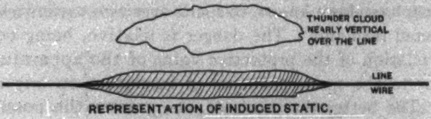
THUNDER CLOUD NEARLY VERTICAL OVER THE LINE
LINE WIRE
REPRESENTATION OF INDUCED STATIC.

FIG. 19.—Thunder cloud nearly vertical over line

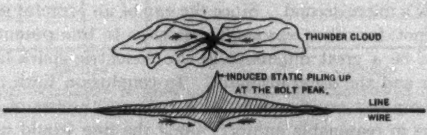

FIG. 20.—Thunder cloud discharging

Possibility of Using Lightning Arresters to Protect Against the Bolt-Peak. In the foregoing theory it is indicated how the induction on the line from a cloud may extend over as much as a mile, yet when the lightning bolt takes place it may cause a bolt-peak on the line confined to a very short length. All the experience with broken insulators and damaged poles show a narrow localization of the trouble on one to four poles, the latter only for wooden poles and direct strokes on the line. This will be discussed further, under direct strokes. It is conclusive that in order to be effective, lightning arresters to protect the line against the bolt-peaks of static induction would have to be placed with comparatively short distances between them. What this spacing should be can only be guessed at.

Some observations lead one to say that it would be necessary to have an arrester at every tower or perhaps every other tower. Insulators have been known to spark over two towers away from a protected insulator. The danger is relative, being controlled by the relation of the protective value of the apparatus at one insulator to the spark potential of insulators on any adjacent tower. The better the insulator, the greater the possibility of protecting at some distance away.

It is doubtful if any known arrester situated on the line at some distance from the bolt-peak would be able to trap this moving charge as it rushed by in the travel toward the bolt-peak. This doubt comes from a consideration of the dielectric-spark-lag of any gap of an arrester and the velocity of movement of the charge along the line. With an assumed distance of 1000 ft. (304 m.) between the arrester and the *bolt-point* and the charge of electricity rushing toward the bolt-point at the rate of 180,000 miles (590,550 km). per second, the dielectric-spark-lag of the arrester would have to have the impossible value of less than 1/900 of a micro-second. Since the gap of an arrester so applied should not, for other reasons, be set close to line potential there will not be a great difference in the dielectric-spark-lag of the arrester and the usual insulator. In conclusion both operating and laboratory experience to date indicate the use of lightning arresters in reasonable numbers along the line would not give a protective value sufficient to warrant their installation. The cost of a lightning arrester varies directly with the voltage and it would require more conviction than the evidence now in hand gives, to warrant the expense.

Trolley Line Arresters. This discussion does not cover the case of lightning arresters, along a trolley line. Lightning arresters along a trolley circuit are in reality, to assist in the protection of car apparatus. That they protect the line also, to a certain extent, is an incidental matter. Furthermore the circuit voltage being low the cost of the arrester is not such as to make its use in considerable numbers along the line prohibitive.

Why "Spill-overs" Occur Usually on Only One Insulator. With the foregoing theory of the static charge on the line in mind, an explanation of the frequent limitation of failure to one insulator can be added. In this theory any high frequency which may be superimposed on the charge when it is freed by the cloud discharge will be neglected. At the instant that the charges on the several wires of the transmission line are freed, there is probably only a slight inequality in the potential of the lightning on the several wires or phases. Due, however, to this inequality in the lightning potential and also to the variable values of dynamic potential on each phase at any instant, the conditions frequently favor the failure of only one insulator. No doubt in some cases variations in the dielectric strength of the insulators may also play a part.

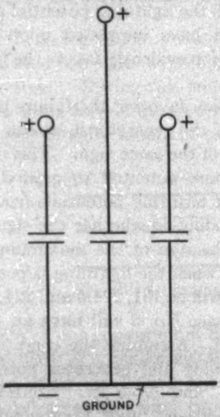

FIG. 21.—Capacity of lines to ground for lightning

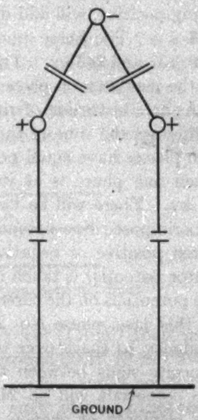

FIG. 22.—Capacity of lines to ground, one wire grounded

In order to show the effects of the instantaneous values of dynamic potential on the spill-overs of insulators, two numerical problems are chosen; one of these problems shows the extreme conditions favoring the failure of one insulator, and the other problem shows the extreme condition favoring the failure of two insulators simultaneously on different phases. In a circuit in which 60 kv. effective is impressed, the peak potential of the generator wave is 49 kv. to ground. Choosing an instant when phase No. 1 is zero, phase No. 2 has a negative potential of 43 kv. to ground at that instant and phase No. 3 of 43 kv. positive. If at this instant a lightning potential of 200 kv is impressed on the line, the potentials of the generator waves would be added or subtracted to this lightning potential. Since the lightning potential exists between lines and grounds, the addition must be made to the instantaneous values of the " Y " potentials of the generator. Phase No. 1 being at zero, the total potential will be 200 kv. Phase No. 2 being at negative potential, will have a value of 200 kv. minus 43 kv. = 157 kv. Phase No. 3 being positive, will add directly to the lightning potential giving 243 kv. The three phases then have impressed upon them 200, 157 and 243 kv. This condition evidently favors the failure of the insulator on phase No. 3.

As an illustration of the condition favoring the failure of two insulators the time in the cycle of the generator is chosen when two phases have equal potentials of the same sign. This occurs when one phase is at its maximum potential to ground, *i.e.*, 49 kv. There will be two sets of resulting potentials from the superimposed line potential according to whether the signs are taken positive or negative. If the sign of the maximum generator potential is taken negative when the lightning is positive, the potentials on the three phases will be 151, 224.5 and 224.5 kv. In this case, phase No. 2 and phase No. 3 will have an equal tendency to spark over to ground. Assuming the condition of opposite signs between the lightning and generator potential, the potentials will be 243, 175.5, and 175.5 kv. Considering the elements of chance, the conditions favor very much the failure of a single insulator. This statement will be evident if one considers that at the time two phases have equal potentials, they are both changing their potentials at a rapid rate in the opposite directions. Even for this instant, the chances are one in two that the lightning will have the opposite polarity and not be additive.

Turning now to the lightning charges on the lines, there appears instantly at the time of a cloud discharge two effects which influence the potentials of the different phases. One of these effects is electrostatic and the other electromagnetic.

In releasing the potential strain on one wire relative to ground, the strain on the other wires is reduced, although there may be no change in the charges on the other wires. This is due to the change in static capacity of the system. Before the single insulator breaks down all the wires are acting as one plate of a condenser with the ground as the other plate. (Fig. 21.) On account of the great distance to the ground the static capacity of the wires is relatively small. As soon as a single conductor is grounded (Fig. 22) it becomes oppositely charged and the static capacity of each of the other conductors is relatively increased by the proximity of this grounded conductor. The same charge in a larger static capacity lowers the voltage according to the fundamental equation $V = \frac{Q}{C}$.

The lowering of the voltage retards the spark by the value represented on the hyperbolic curve of dielectric-spark-lag versus time. During this added interval the static charges left on the wires have time to spread in both directions along the wires and thereby lower the potential strains still further. The capacity of one conductor of three at six feet (1.8 m.) apart used as one plate of a condenser, with the ground 30 ft. (9 m.) away as the other, is 0.0069 microfarads. This same conductor grounded gives an added capacity to each of the other conductors of 0.0025 microfarads or a total increase of 143 per cent.

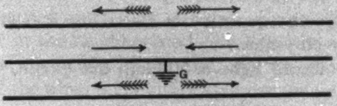

Fig. 23.—Electromagnetic induction between lines

The electromagnetic effect is much greater apparently than the electrostatic effect of the change of capacity.

With the middle wire grounded as shown in Fig. 23 there will be a rush of current toward the grounded point. These two currents represented by the non-feathered arrows will induce extra electromotive forces in the adjacent wires which give an added impulse to relieve the potential strains on the other wires. The induced potential is represented by the feathered arrows.

Apparently these two factors are so important that in the systems studied the majority of insulator "spill-overs" are limited to one insulator. However it is evident that the phenomenon of reduced voltage, due to these factors, has its limitations and more than one insulator may be caused to fail.

Numerical Conceptions of the Factors of Induced Lightning. There is so frequently formed a misconception of the functions of a lightning arrester in discharging lightning and dynamic currents that the following calculations are given to aid in defining the requirements. Especially in foreign installation has it been brought many times to the writer's attention that certain type of arresters were operating satisfactorily, the judgment being based entirely either on the number of times the arrester had sparked or, on the brilliancy of the spark. Neither of these qualities are *necessarily* a measure of the value of the arrester. High resistance arresters with small series gaps spark easily without giving much protection. Arresters allowing considerable dynamic to follow may give both brilliancy of spark and noise in discharge and yet not be very effective.

The following approximate assumptions are made: One mile (1.6 km.) of line having about 0.012 microfarads capacity to an overhead grounded wire is charged to 100,000 volts potential by lightning.

In this charge the quantity of electricity is 0.0012 coulombs and the energy 60 joules.

This energy would light a 50-lamp arc circuit for less than 0.004 second.

It would light a 16 c.p. incandescent lamp for about one second.

At 10 cents per kw-hr. it would cost 0.000016 cent.

It would raise one pound (0.45 kg.) weight about 40 ft. (6 m.).

The quantity 0.0012 coulombs traveling along a line at its natural rate of speed, 180,000 miles (590,550 km.) per second, represents a current wave of about 200 amperes and would have to be discharged at that rate if the potential at the end of the line is to be kept down.

If the charge oscillates at 10,000 cycles per second it represents a current of about 12 amperes.

If allowed to discharge at the rate of one-half ampere it would require 0.001 second to reduce the potential to about half, *i.e.*, 50,000 volts; if at the rate of 600 amperes the time would be reduced to 0.000001 second.

When this energy of discharge is transformed into chemical energy its relative value sinks into still further insignificance. For example, it would deposit only 0.0000013 grams of silver. For the disassociation of aluminum it would give a number of the same order.

If all the energy were dissipated in heat in the aluminum arrester instead of being absorbed mostly in chemical action, it would raise one gallon (3.8 liters) of electrolyte only 0.0037 deg. cent.

These quantities are quite small, still it takes much less energy to puncture a small hole in any ordinary insulation. If the charge on the line were at a million volts, the foregoing values would still be small.

If a good lightning arrester with a high rate of discharge, a large electrochemical absorption capacity, a large heat capacity, and taking practically no dynamic current, makes no fuss or noise in the ordinary discharge, or does not permit of a large puncture of a paper in a series gap, it is no indication that the arrester is not performing its function of protecting.

Some Observations on Direct Strokes. There is a possible gradual increase in intensity of lightning potential on a line varying from a negligible impulse up to the irresistable lightning bolt derived from a dozen large clouds. Theory and observation, however, indicate that there is, in general, a clear cut demarkation between the induced and direct strokes. Unless there is some high conductor in the neighborhood of a line, the conditions of cloud discharge, the height of the line, and the good horizontal conductivity of the wires favor either striking the line or striking at some distance from it. The factors of suddenness of formation of the thunder clouds, the particular localization of cold air coming in contact with jets or spouts of moist warm air, relative distances, and so forth have no doubt a strong bearing on the subject. The theories of cloud formation given by Dr. Steinmetz a number of years ago satisfactorily explains many of the various phenomena of direct strokes. This part of the subject is beyond the scope of this article.

It is of scientific interest to know how close to a line a lightning bolt may strike and cause a certain dangerous rise of potential, and how this potential is raised as a side-stroke from the main discharge, may lick out and touch the line, and how these side-strokes may vary in volume from a tiny static discharge up to the great volume of a direct bolt.

It is of practical value to determine in general; first, the minimum distance that may exist between the main discharge and the bolt peak without causing a spill-over on any particular type of insulator; second, in the next step in severity, to determine the minimum distance between the main stroke and the bolt-peak on the line that may exist without causing insulators on two separate phases to spill-over simultaneously and cause a short-circuit of the power; third, to determine if it is practicable ever by means of lightning rods extending above the poles or towers to conduct the majority of lightning bolts down through lines of reasonable spacing, without causing a spill-over of the power.

These broad engineering problems of protection must be solved before the natural growth of electrical power transmission can advance much further toward perfect continuity. Each year an advance is made in some of the more obvious problems of protection. The problem of protection against lightning in its last stage—that is, protection against a direct stroke—is not the manufacturer's problem alone. There is nothing obvious in protective apparatus to sell and, therefore, the manufacturer's interest must be simply to widen the field of use of transmission apparatus by giving immunity from trouble. No single transmission company can afford to spend the money and time necessary to solve these problems, each can help by making systematic observations. Judging from the present outlook, however, no rapid advance will be made until the matter is taken up formally and systematically with the efforts centralized on some few particularly favorable systems, the expense and work being shared possibly by an association of transmission companies, and the manufacturers of electrical apparatus. The coöperation of the U. S. Weather Bureau, the Carnegie Institute, and such other societies interested would be of value.

Some of the Effects of Direct Strokes. Some of the effects of direct strokes observed are given as follows: Where direct strokes occur, a short-circuit of the power usually accompanies. Insulators are usually shattered. If the direct stroke did not do it, the power arc would; it is thus impossible to attribute the cause entirely to the lightning. On the metal tower lines or where the insulator pins are grounded, the arcs from direct strokes are confined usually to one tower. When, however, wooden cross arms and wooden poles or towers without metal grounding wires are used the direct bolt usually spreads over several poles or towers. The difference in these actions is due to the fact that the sparking distance for the case of the grounded pin is limited to the arcing distance of the insulator, a distance of the order of one foot (0.3 m.). The spark takes place before the charge can spread horizontally along the line. When, however, the sparking distance is 30 ft (9 m.) or more down the poles the charge has time to spread horizontally along the line (or perhaps the main bolt forks) and this divides between two or more poles or non-conducting supports. There is less liability of a direct bolt striking a line separated from the ground by wooden poles without lightning conductors but when such a line is struck the damage to the wooden poles frequently requires renewals. Other things being equal, the transmission line is probably somewhat more liable to be struck than trees or other poorly conducting objects near and just as high because of the possibility of the electricity gathering horizontally along the wires and by the concentration of potential this should favor the formation of discharge from this point. In the case of the metal towers, which act as lightning conductors, there is, I believe, much to favor this path for the lightning bolt. Only two instances are known of lightning striking through the lines and burning them off midway between poles, without damaging the poles. It is probable that these were very sudden heavy strokes.

Where lightning will strike, has been the subject of speculation by a number of scientists. Dr. Steinmetz has expressed the opinion that the charge follows the paths in the atmosphere that are under the greatest stress—this stress not being produced by the charges on a definite cloud and earth but by the accumulated charges at every point in the atmosphere.

From the meagre data at hand and from the most plausible speculations the path of lightning will be decided by such factors as:

1. The charges in the clouds.
2. The ionization of the intervening layers.
3. The shortest path of the stroke.

This ionization of intervening layers of atmosphere depends upon such factors as moisture, temperature changes, and unknown sources. The effect of the local stresses on the path probably depends greatly on accidental conditions of air currents, funnels, etc.

It seems reasonable, however, to assume that there are certain layers of air not locally ionized but put under heavy static strain by the accumulation of electricity in the clouds and, therefore, the effect of the shortest distance between points must come into play. Everything else being equal, the highest conducting point must be struck by lightning.

It seems probable that some other factors bearing on the direction of lightning strokes may later be recognized. Using the information and theory at hand it is the relative prominence of the second and third factors, namely, local ionization in the atmosphere versus the shortest path, which are of vital interest in the design of a circuit to be absolutely immune to lightning. The answer must be found to the question, what must be the spacing and height of the overhead grounded wires to prevent the local ionization between lines directing a lightning bolt on to the transmission wires?

If there is a wind it is inconceivable that air near the earth could be very highly ionized. It is constantly being rolled over in contact with the earth which would tend to keep the potential down and somewhat uniformly distributed.

If there is no wind and the atmosphere between widely separated overhead grounded wires becomes charged locally to a high potential there is the electrostatic force tending to draw the charges in the free moving atmosphere toward the grounded wires and thus discharge it. So far as these theories can be depended on they show that the law of the shortest path is the predominant factor near the overhead grounded wires. The spacing between the protecting grounded wires and the power wires must be determined. This distance, to be safe to the power wires, is to be determined by taking into account the type and spark potential of the insulators, also the corona losses from the power wires.

An endeavor has been made in the foregoing paragraphs to present the general nature of the problem of protection of transmission lines from lightning. In the extreme, there is at present no way of preventing some lightning affecting the operation of a transmission circuit. And there has been little done to minimize the destructive effects of direct bolts. There is, however, something that can be done to minimize the effects of light strokes and induced strokes, and much can be done to prevent damage to the circuits and avoid interruptions of service.

What has Been Done to Protect Lines. First. The overhead grounded wire has been used. Great stress has been laid on the electrostatic screening by the overhead wire but the electromagnetic induction has been somewhat lost sight of. For example the practice of grounding every five poles on wooden pole lines may not be sufficiently frequent. A single overhead wire does not give perfect screening from electrostatic cloud induction. If, moreover, this screening charge must run a considerable distance to get to earth it may induce nearly full potential, by electromagnetic induction, on the power wires. To endeavor to get concrete ideas on this value experiments were made in imitation of the line conditions.

The relations of the overhead grounded wire and a transmission wire are shown diagrammatically in Fig. 24. At the instant the electrostatic lightning charge is freed on the overhead grounded wire, the charge divides and rushes toward the nearest grounded point as shown by the arrows on the wire marked 1. Three condensers represent the distributed capacity of this wire. In the circuit of the transmission wire, marked 2, there are three gaps marked *Q* which represent the gaps at the insulators. With a given discharge of potential on the overhead grounded wire, the question is, what potential will be induced on the insulators?

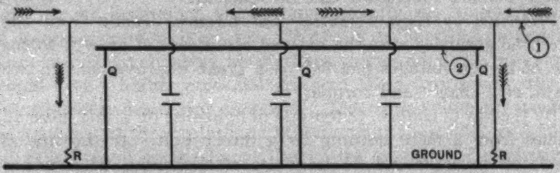

FIG. 24.—Diagram of overhead grounded wire on line

Fig. 25 shows diagrammatically an equivalent circuit in the laboratory. It consists essentially of a loop within a loop.

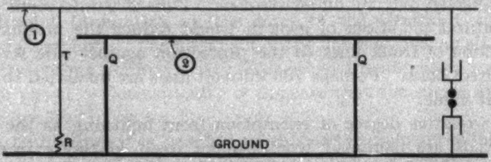

FIG. 25.—Laboratory connection in imitation of grounded wire

The leyden jars at the right were charged by a static machine and suddenly discharged. The following values are given for two concentric loops having a total length of parallel wire of approximately 200 ft. (60.96 m.). With an impressed potential at the jars represented by a gap of 2.55 inches (6.47 cm.) the induced potential on the line loop was 2.04 inches (5.18 cm.). The first test was made with a distance between loops of one foot (30.4 cm.) and the second test with a distance of two feet (60.9 cm.). They both showed the same equivalent-needle-gap of 2.04 inches (5.18 cm.). That the greater distance should give the same induced potential was due perhaps to an accidental condition of partial resonance. The potential on the line was 80 per cent of the potential of the ground wire. This suffices for the present to emphasize the value of frequent grounding of the overhead wire. There is more work to be done before definite conclusion can be reached.

Protection by High Potential and Chance. Aside from the overhead grounded wire the natural conditions of growth to the use of higher voltages has led to a great improvement in two ways, *viz.*, chance and corona.

By the law of chance, potentials of lightning on a line have all values from a mere nothing to a direct bolt. If the line is insulated to withstand 25 kilovolts all lightning within that range is harmless to the line, but there will be, in general, numerous impulses of higher potential. If the line is insulated to withstand 200 kilovolts then there is added to the sum of the previously harmless impulses all those lying between 25 kilovolts and 200 kilovolts and the number above 200 kilovolts is comparatively few. Following up this reasoning and assuming the truth, in general, of the statement previously made that the lightning must either strike the line or else strike some distance from it, there must be a certain degree of insulation for the line which withstands the greatest induced stroke and is, therefore, affected only by direct strokes. Thus it would seem that the natural conditions of growth would reduce the problem of protection of trunk lines to the protection against side strokes and direct bolts. Perhaps 100 kilovolt lines are insulated to this critical value.

This relative degree of exemption from lightning as the line potentials are increased would make itself glaringly evident were it not for another law entering. An increase in potential accompanies naturally an increase in the length of line, and the increase in length increases directly the exposure to lightning.

Protection by Corona. The second way the higher voltages give a greater degree of immunity is through the loss of electrical energy in corona. In the use of high potentials, the critical potential of brush discharge falls naturally only slightly above the value of impressed potential. In fact in some recent propositions it has been necessary to increase the diameter of the line wire to keep the brush potential above the impressed potential. When this condition exists then all superimposed potentials above the corona potential cause a self-destructive loss of the electrical energy in such a surge. This electrical energy is transformed into chemical energy—ozone is formed. The formation of chemical energy in ozone is not a reversible process. The suppression of the surge is complete and effective. The use of the overhead grounded wire gives a great degree of uniformity of corona discharge along the power wires. The grounded wire, by its proximity, thus relieves greatly the concentration of corona around an insulator. Without the overhead grounded wire, the relatively short air distance to ground at the insulator would give a higher potential gradient there than at any other point between insulating supports. The corona discharge would be strongest at the insulator and furthermore the insulators would be called upon to discharge the entire quantity of electricity between insulators. Heavy brush discharge easily changes into spark discharge, therefore, the insulator is more liable to failure without the overhead grounded wire.

If the formation of brush discharge has no time lag after the application of potential, then the rapid collection of static toward the bolt-point at the instant of cloud discharge, will lose its vicious electromagnetic inertia by discharging at every inch along the line. At the time of writing no specific measurements have been made on this subject of lag of brush discharge by the writer. Some information may be gleaned from the following paragraph.

It has been stated that surges of high potential can not cross the Rocky Mountains on the lines of the Central Colorado Power Company. The high part of the line is at such an altitude that the corona voltage is very little above the impressed voltage of the power. Consequently it appears that the surges at this point are lost in ozone.

On trunk lines it is possible to choose the diameter of the line wire and potential such as to suppress all induced potentials from cloud lightning and all internal surges between lines. This leaves still the problems of caring for a lightning stroke near a station, and a direct stroke on the line.

On the Design of Insulators. In the exemption from interruption the design of the insulator must play an important part, especially is this true if it is expected to get the beneficial action in full of the insulator protector described hereinbefore. The test for insulators has always been a gradual applied potential.

It is desirable to have the insulator flash around the petticoats rather than puncture. Testing out the separate petticoats and obtaining a flash-over at the limiting potential does not insure that, when assembled, the insulator will spill-over rather than puncture. Furthermore, a design which may spill-over on gradually applied potentials may puncture on suddenly applied potential. Investigation of the laws of flash-over have been made.

Line Construction and Design from a Protective Standpoint. Most of the elements of design are determined by mechanical requirements and cost of materials with reference to final economy. A discussion of either of these factors is beyond the scope of this paper. In any engineering problem there are always conflicting conditions to be met and the result is a compromise between these factors. In the following paragraphs an endeavor is made to show the elements entering into the problem of protection against lightning. One may choose wood or iron according to the voltage, cost of materials, kind of service, and locality. What is good practice in California may be poor practice in Brazil. What is good practice in the East may be poor practice in California.

In the different forms of construction the elements entering to affect the protective qualities against lightning are:

1. Wooden poles.
2. Wooden pole with vertical wire or metal tower.
3. Lightning rod extending above the pole or tower.
4. Wooden cross arm.
5. Wooden pin.
6. Wooden cross arm with metal pin.
7. Metal cross arm with wooden pin.
8. Grounded metal pin.
9. One overhead grounded wire.
10. Two overhead grounded wires.
11. Location of overhead grounded wires.

1. Wooden poles. From the meagre information of definite character that observation has given and from the theory, the statement is warranted that wooden pole lines are a little less liable to be struck than metal towers. When struck, however, the damage is frequently sufficient to necessitate renewals of poles. On trolley lines the wooden pole acts as an additional insulator against dynamic potential and is a valuable addition to lightning protection.

2. A wooden pole with a wire run vertically up its side is an equivalent, from a protective standpoint, of a metal tower with wooden crossarms. The presence of the vertical wire prevents damage to poles by direct stroke.

3. A lightning rod extending above a pole or tower gives, theoretically, a degree of immunity from the effects of direct stroke. No one has been able to observe whether the degree of protection warrants the expense. Assuming that a tower is struck it seems rather short-sighted to spend a considerable amount of money in overhead grounded wire and not add just a little more in an endeavor to keep the intense flame of the lightning stroke above and far enough away from the line to prevent its blowing between phases and causing a short circuit. If the insulation from each phase to ground is not sufficient to hold back the induced lightning when a tower is struck then the lightning rod is a useless expense. If the insulator is the smallest one designed for the specific voltage of the line and is set on a grounded iron pin, experience teaches quite definitely that the insulator would spill-over. Strokes 100 ft. (30 m.) from the line have caused such failures. However, with better insulation and with the possibilities of getting a certain number of light strokes or side strokes it is warrantable, it seems, to add the lightning rod in some cases.

4. Wooden crossarms, when they can be used, add enormously to the insulation of an insulator against lightning. Elsewhere the writer has given tests to show that a crossarm even when wet gives good lightning protection. Its use on high potentials where it is subject to burning off, if a failure of an insulator takes place, is justifiable only if by its use the number of interruptions become practically nothing. It is usually better practise to ground the pin and interrupt the power for an instant more frequently, than to use the wood, and undertake the great expense and loss of time in locating and repairing a less frequent fault in the line. The advent of the arcing ground suppressor also throws the argument strongly in favor of the grounded pin. In dry climates and with medium voltages, a line wire may be carried for days in contact with a wooden crossarm and not burn it off.

5. Wooden pin. On account of lack of strength the wooden pin has its limitations. On high voltages it is frequently digested by the static from the line. The wooden pin, has the same value as the wooden crossarm in giving greater spacing between metal parts and thereby cutting down the potential gradient. It increases the dielectric strength of an insulator.

6. Wooden cross-arms with metal pins. In this case it seems that the use of a metal pin instead of a wooden pin is permissible even from a protective standpoint. The metal pin has only its isolated capacity to draw a discharge from the line. The charging current to the pin can be obtained from a harmless corona streamer and there seems to be no appreciable danger of these streamers starting a grounding arc.

7. Metal crossarm with wooden pin. This is a combination not often found. Where the smallest possible insulator is used the wooden pin, where possible, will be of considerable value in increasing the insulation.

8. Grounded metal pin. This is the usual condition on high-tension lines dictated by mechanical requirements. As already indicated in a negative way in the discussion of wooden supports, the grounded metal pin requires the use of an insulator of larger dimension to give the same dielectric strength to ground as the normal insulator with a wooden pin. When the relative cost of the insulator to the rest of the line construction is taken into account, a large insulator, giving a large factor of safety, is justified. Where continuity of service is of great value the extra sized insulator is a good investment. Where economy is necessary it is usually better practice to put the investment in the insulation rather than in the overhead grounded wire.

9, 10 and 11. Overhead grounded wire. While engineers are generally agreed that overhead grounded wires give a considerable degree of protection—sufficient to justify the expense of their installation—there is almost nothing of definite character that has been given. Calculations on the screening effect with one grounded wire well above the line wires show a reduction in induced electrostatic potential of about 50 per cent. Laboratory tests give values of the same order. Two overhead grounded wires are better than one—the extra protection given is unknown. So far as induced charges are concerned it is possible to arrange tests which will give fairly definite values. It will probably be done some day. The conditions of protection against direct strokes are not amenable to experimentation and must be left to observation.

Conditions Without the Arcing Ground Suppressor

The practice followed by operators of transmission lines has varied considerably. The following classification is made:

1. The accidental arc to ground may be extinguished by the wind or other favorable condition.

2. The power may be discontinued to clear the fault.

3. The accidental arc to ground may be allowed to play until (*a*) It breaks the petticoats off the insulator, or (*b*) until the surges damage some apparatus or other insulator and cause a short-circuit, or (*c*) until it burns off the power wire.

1. *An Arc to Ground Extinguishing Itself.* Dr. Steinmetz has given some equations of the relation between current and arc length. These equations relate to conditions approaching unity power factor or lagging currents. There are no equations for arc lengths with the currents leading the e.m.f.

Since the current from a phase to ground supplies the quantity of electricity for the unbalanced electrostatic condition it is leading the e.m.f. to ground and produces, therefore, an unstable arc. During tests of a 20-mile (32 km.) 33-kilovolt transmission line, unloaded, with an average current to ground of 2.5 amperes, it was difficult to maintain an arc from wire to pin on an insulator designed for 45,000 volts, even when there was no wind blowing. To carry on the tests it was necessary to shield the arc from the wind and shorten it down to insure its continuance. This is a point in the design of a system that is well worth considering.

During the past lightning season there have been several cases of arcing grounds on the lines of the Southern Power Company that have cleared themselves. In the tests on the Schenectady Power Company's lines a small gap to ground was made between electrodes that sprung apart as soon as the arc burned off a string. When these electrodes were pulled away suddenly to a distance of four or five inches the arc to ground was frequently extinguished. The wave shapes of current in the arc vary widely depending on accidental shapes of the arc, its position relative to the vertical, the magnification of harmonics, etc. This matter is treated elsewhere. One of the important factors tending to extinguish the arc is the weakening or cooling of the arc by any means during the wave when the current is decreasing toward zero. This factor is especially important at the initial instant when the arc is struck. If the spark takes place during the period of decrease of potential there is a probability that insufficient metallic vapor will be formed to carry the conductivity over the period of zero current, which period is lengthened by the presence of electrostatic capacity. This condition together with the aid of a favorable wind perpendicular to the line cannot be depended upon except in rare cases.

2. *Discontinuance of the Power to Interrupt the Arcing Ground.* Since the dangerous nature of an arcing ground has become so generally appreciated, it has become the practice on many systems to open the main switch and shut off the power for a minute in order to rid the line of this electrical octopus. It is a heroic method but lacking other means, it is nearly always advisable.

3. *When an Arcing Ground is Allowed to Play.*

a. It cracks off the petticoats of the insulator. This cracking is due to unequal heating of the porcelain. In order to determine the characteristics of this action several samples of insulators were tried with different values of current. Some of the conditions of arc are shown in the accompanying photographs. The following summary covers most of the observations:

FIG. 26.—Test 8

Picture of insulator after four-ampere arc had played over it for 10 minutes

Dimensions of Insulator. Total height 6 in., (15.24 cm.) diameter of head $6\frac{3}{4}$ in. (17.2 cm.) diameter of middle shell 5 in. (12.7 cm.) diameter of bottom shell $3\frac{1}{16}$ in. (7.77 cm.)

FIG. 27.—Test 9

Same type insulator as in test 8. Four ampere arc played for about one second—instantaneous photograph—insulator uninjured.

The arc does not rise under the two lower petticoats but it can be seen lying against the under surface of the upper petticoat to where it rises around the edge at the right and makes a high loop above the insulator back to the tie wire.

The arc is usually shifting from one place to another on the petticoats due probably both to local air currents and to the electromagnetic forces. As a four-ampere arc licks around the edge of a petticoat, little slivers of porcelain are thrown off successively with a snappy noise. It requires several minutes to wear away a petticoat this way. Sometimes the arc will rise under a petticoat and run around part way underneath, hugging the porcelain, before it rises around the edge. This is especially true in the case of the flatter upper petticoat. The arc of four amperes must remain a considerable fraction of a minute in one place to split off a large piece of the petticoat.

Several illustrations are shown, Figs. 26 to 32 inclusive, with explanations which illustrate the foregoing summary. The circuits were inductive with a lagging current from an arc light transformer. This gives the arc a stable condition which is not present when the insulator is in normal operation on the line. The test gives a more severe condition of heating of the porcelain than would obtain in practical use of the insulator.

Fig. 28.—Test 11

Same type insulator as test 8—four-ampere arc played for about one second and then blew out—time exposure of entire phenomenon—insulator uninjured.

The dissipated metallic vapor in the loop over the insulator, which caused the extinguishment of the arc is plainly visible in the photograph.

Fig. 29.—Test 14

Same type insulator as in test 8—four-ampere arc on for about 1¼ minutes—time exposure of entire phenomenon—the insulator was considerably broken, especially the middle shell, one side of which was completely broken away. The porcelain was also heated red hot in spots.

The large flame in this photograph is not due to a large arc but to the movement during the 1¼ minute of the same arc as in the previous tests. The maximum length of the arc was about two feet (60 cm.)

It will be shown later in tests on burning of line wires that large currents become safer to the insulators than certain smaller values due to the fact that the electromagnetic forces tend to throw the arc out into a long loop away from the porcelain.

b. The surges damage some apparatus or other insulator and thus cause a short circuit.

The *nature of the surges* produced by an arcing ground are not very well understood. Arcing grounds on some systems have been allowed with impunity to play ten hours and not produce any

FIG. 30.—Test 15

Total height of insulator 14⅛ in. (35.8 cm.) diameter of head 14 in. (35.5 cm.) diameter of middle shell 9⅛ in. (23.13 cm.) diameter of bottom shell 7⅛ in. (17.9 cm.). 2½-ampere arc played about two seconds—instantaneous exposure—the insulator was uninjured.

The arc follows the surface of the porcelain under every petticoat. From the middle petticoat it rises vertically to the upper petticoat, turns to the right, passes back, then to the left to the opposite outer edge.

FIG. 31.—Test 17

Same type insulator as in test 15—2½-ampere arc played about four seconds and then blew out—time exposure of entire phenomenon—the insulator was uninjured.

The movement of the arc is shown by the hasy streaks. The denser parts indicate a greater or less halt in the movement.

noticeable damage. On the same circuit an arcing ground for as many seconds has produced short-circuits in the heart of transformer windings and caused spill-overs on transformer bushings. Although exact values of capacity and inductance to cause trouble are not known, there are several generalities which can, from experience, be stated positively. Every piece of apparatus has its own natural frequency—every coil its own, and different parts of a system each has its own natural frequency. If the frequency derived from the arcing ground corresponds to the natural frequency of some local circuit, resonance will result and unless the energy of resonance is absorbed by the natural conditions of load or by a special surge protector, a high localized potential will result. A considerable amount of data has been collected on specific conditions but the amount and nature of these tests and theories carries the matter outside the scope of this paper. Some generalizations regarding the frequencies set up by an arcing ground may, however, be added. In any circuit where electrostatic capacity predominates to give a leading current, the arc will tend to be extinguished and relighted at the natural frequency—in other words, the arc magnifies every slight change in the circuit. Harmonics that are invisible in the e.m.f. wave often become in the arc current more prominent than the fundamental wave of the generator. The magnification of the higher frequencies depends greatly on the instability of the arc. The instability of the arc, in turn, depends on the relative values of arc length and arc current, also on the local conditions of cooling, and rectification effects of the metal vapor.

c. The Arc to Ground Burns Off the Line Wire. In the early work on the arcing ground suppressor, experiments were made to determine if the line wires could be burned off before the protector could operate. It was immediately evident that the burning in two of a line wire took so long that it would not be a factor in the design of the protector. An anomalous condition was encountered, however, which is of importance. Medium large currents will not burn off a wire where less current will.

FIG. 32.—Test 18

Same type insulator as test 15—2½-ampere arc played for about eight seconds and then blew out—time exposure of entire phenomenon—the insulator was uninjured.

In this case, although the exposure is twice as long as in the previous test, less trace of the arc is visible. This is explained by the fact that the arc was more constantly on the move.

Specifically, first, there is a certain limit of current which can be carried without overheating the wire at the crater of the arc. Second, a little greater current will soften the copper and the wire will separate. Third, a still greater current introduces electromagnetic forces which are sufficient to drag the arc out along the wire. This movement of the arc carries the arc-crater to new positions on the wire before the copper reaches a dangerous temperature. Once the arc is lengthened it sets up air currents which coöperate with the electromagnetic forces to keep the arc crater moving in and out along the wire. It is only when some accidental condition occurs which holds the crater in a spot for considerable time that the wire will fail.

These accidental conditions rarely occur. Fourth, when the arc current becomes very large the wire is again in danger of melting due to the fact that the energy loss at the crater is so great that if the crater tarries a moment in its movement the damage is done.

Experiments on Burning Off of Line Wires. Same numerical values are given below. The source of power was alternating current at 2,300 volts. The copper wires were stretched horizontally under two degrees of mechanical tension. Perpendicularly underneath each wire an iron insulator-pin was placed, leaving a gap of one-half inch. The arc was started by means of a fuse.

FIG. 33

Arc of 10 amperes on the line wire. The arc is about 2 in. (5.08 cm.) total height. The line wire is shown by the short central horizontal line. The wire burned off in 2.5 minutes.

FIG. 34

This arc was also at 30 amperes. It shows at the instant of exposure, a vertical and horizontal loop. Later the arc rose to nearly three feet before it broke.

A No. 6 B. & S. wire carried three amperes for 20 minutes without damage to itself. The wire became red hot, but the 20 lb. (9 kg.) of tension was not sufficient to break the wire.

Under the same conditions a current of six amperes caused the wire to separate in 2.3 minutes.

Next, a No. 4 B. & S. wire was used under a tension of 180 lb. (81.6 kg.)

It carried six amperes two minutes without damage. The wire around the crater was heated to a dull red; 8.4 amperes were then applied for two minutes without damage; 12.2 amperes were then applied for 0.7 minute without damage.

Twelve amperes being the limit of the series choke coils in use, a water rheostat was substituted and the current was increased to 30 amperes with the idea of getting quicker burning. This did not occur. The arc left the shortest distance between the wire and pin. One crater traveled out along the wire and the other traveled vertically down the pin to its base. The result of this was an extinguishment of the arc in about one-quarter minute each time the potential was applied. The wire did not reach even red heat on account of the constant shifting of the crater.

Being impossible with the available potential to burn off the wire with 30 amperes, the current was reduced to 15 amperes and the wire separated at a point about one inch (2.5 cm.) to the right of the point vertically over the pin in just one minute. The electromagnetic forces moved the arc out this far, but the resisting force exerted by the crater prevented any further movement.

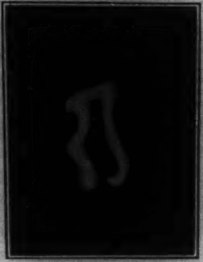

FIG. 35

This arc was also at 30 amperes initially. It was taken at a time when a long loop had just short circuited itself at about half way up its length. The upper part which was short circuited shows less metal vapor. The height was about three feet (91 cm.).

FIG. 36

The current in this arc was 15 amperes A time exposure was made. There is little movement of the craters of the arc. The arc flame rises to a height of over two feet (5.08 cm.).

Subsequently, further tests were made and photographs were taken of the arcs. These are shown in Figs. 37 to 40 inclusive.

CONCLUSION

This paper has been written during hours away from regular duties, and several parts of the original outline have had to be omitted on account of lack of time. A specific problem and its solution have been in the foreground, but it is impossible to separate it from some of the other problems, as they naturally overlap. Some of these subjects treated will be expanded later when the remaining problems of protection are taken up. There are numerous minor problems, but the main problems which are to be solved before absolute continuity of service can be attained are: Protection against direct strokes of lightning, the suppression of short circuits, the suppression of internal surges, and the prevention of malicious or willful interference. More or less satisfactory solutions of all but the last mentioned problem are in sight. Will the demand for great continuity of service warrant the expense involved in getting such service? A collection of a considerable amount of data, shows conclusively, on analysis, that the greatest number of interruptions in lightning infested localities is due directly and indirectly to the single arcing ground around an insulator or in cable systems to a single puncture from one phase to the cable sheath. The arcing ground suppressor, backed up by aluminum arresters, will prevent interruption of service and damage to apparatus in the majority of these cases. This improvement should in general bring the service above the existing standards or requirements. It may be possible to meet the higher demands in the future as they grow.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

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(Subject to final revision for the Transactions.)

TESTS OF ARCING GROUND SUPPRESSOR ON THE 40,000-VOLT SYSTEM OF THE SOUTHERN POWER COMPANY

BY C. I. BURKHOLDER AND R. H. MARVIN

The Southern Power Company experiences every year during the lightning season frequent disturbances and interruptions due to the lightning starting an arc over the insulator to the pin, this arc often breaking the insulators, or sometimes even burning off the line. With the object of extinguishing this arc before it has time to do any damage, an automatic insulator protector has been installed on the 44,000-volt system at the Catawba power house.

The power stations, principal substations and transmission lines of the 44,000-volt system are shown on the map, Fig. 1. This system is three-phase, 60-cycle, non-grounded. There is also a 10,000-volt system, and an extensive 100,000-volt system, not shown here.

The four power stations at present in operation are: Catawba, Great Falls and Rocky Creek on the Catawba River; and 99 Islands on the Broad River. Their rated capacities are: Catawba, 6600 kw.; Great Falls, 24,000 kw.; Rocky Creek, 24,000 kw.; 99 Islands, 18,000 kw.

Two of the lines between Great Falls and Catawba, and the two lines from Catawba to Gastonia are run on steel towers. All the other lines are on wooden poles. All insulators are three-part and are rated at 60,000 volts. The lines are partly copper and partly aluminum. The spacing of the wires is 6 ft. (1.5 m.) triangular.

The insulator protector was installed at Catawba, as this location was convenient, and for some reasons the best. This device consists of three single-pole switches connected between the lines and ground, and controlled by a relay. If any phase becomes grounded, as for example, by an arc over an insulator, the relay causes the switch connected to that phase to close. The phase being grounded through the switch, the arc is short circuited and extinguished. This apparatus was designed by Professor Creighton; its theory and construction are fully treated in his paper, so that no further description is necessary here. The switches are connected to the bus at the Catawba station. The bus is in two sections; one connected to the Charlotte lines, the other connected to the Gastonia lines. The two sections are usually connected together by a bus junction switch. The grounding switches are on the bus connected to the Gastonia lines.

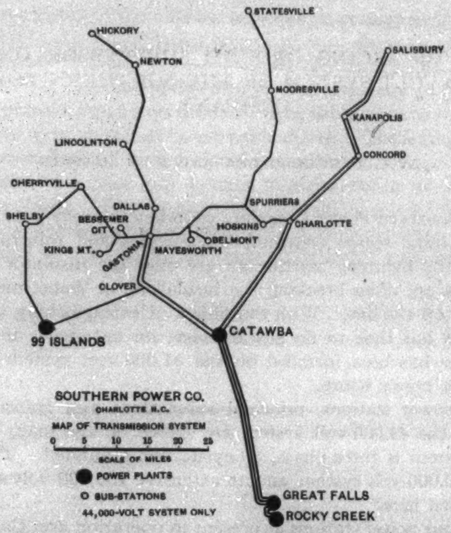

STATESVILLE
HICKORY
NEWTON
SALISBURY
MOORESVILLE
KANAPOLIS
LINCOLNTON
CONCORD
CHERRYVILLE
DALLAS
SPURRIERS
SHELBY
BESSEMER CITY
HOSKINS
CHARLOTTE
BELMONT
KINGS MT.
GASTONIA
MAYESWORTH
CLOVER
CATAWBA
99 ISLANDS
SOUTHERN POWER CO.
CHARLOTTE N.C.
MAP OF TRANSMISSION SYSTEM
0 5 10 15 20 25
SCALE OF MILES
POWER PLANTS
SUB-STATIONS
44,000-VOLT SYSTEM ONLY
GREAT FALLS
ROCKY CREEK

FIG. 1.—Map of 44,000 volt system of Southern Power Company

DESCRIPTION OF TESTS

Object of Tests. The features in the operation of this device, which it was desired to determine were as follows:

1. The time required for the operation of the relay and the various operations of the switch.
2. The total time an arc would exist over an insulator.
3. The time required to extinguish the arc after the switch had closed.
4. The current to ground through the arc over an insulator.
5. The current to ground through the grounding switch.
6. Whether the arc could be extinguished soon enough to prevent breaking or injuring the insulator.

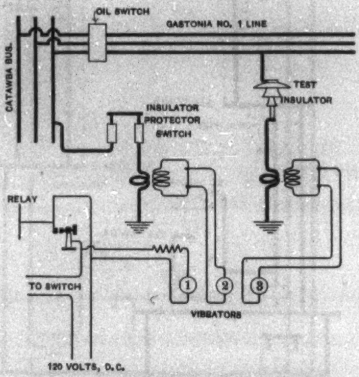


FIG. 2.—Connections of oscillograph

Method of Test. A regular line insulator was suspended by its head from one leg of the No. 1 line going to Gastonia. Its pin was connected to ground through a current transformer. A five-mil resistance wire was tied around the insulator from the head to the pin. On closing the oil switch which connected this line to the bus, the fine wire would start an arc around the insulator, which would hold until extinguished by the grounding switch. The insulator was the same type as is used on most of the lines. The principal dimensions of this insulator are: diameter of headpiece, 12 in. (30 cm.); diameter of intermediate shell, 10 in. (25.5 cm.); diameter of bottom shell, 7 in. (17.8 cm.);

height over all 13½ in. (43.5 cm.). The pin of the insulator was thoroughly grounded by connecting it to the common ground at the station used for all lightning arresters and apparatus.

The connections of the test insulator, grounding switch and oscillograph are shown in Fig. 2.

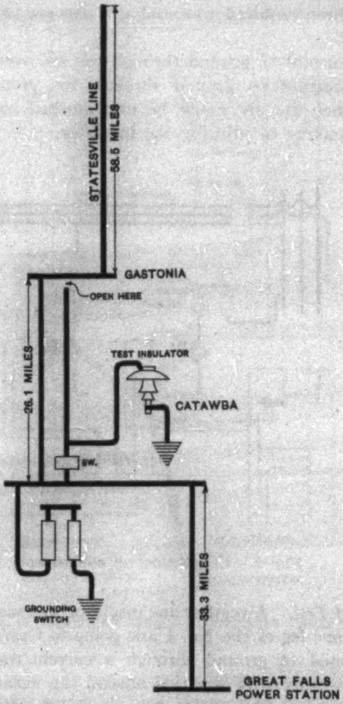

STATESVILLE LINE
58.5 MILES
GASTONIA
OPEN HERE
26.1 MILES
TEST INSULATOR
CATAWBA
SW.
GROUNDING SWITCH
33.3 MILES
GREAT FALLS POWER STATION

FIG. 3.—Connection diagram, tests 1 and 2

Oscillograph Connections. Currents and times were recorded by an oscillograph connected as follows, Fig. 2:

Vibrator No. 1 (the top record) was connected across the contacts on the relay, which would close when a ground occurred.

The closing of the relay contacts would then short circuit the vibrator and reduce its deflection to zero.

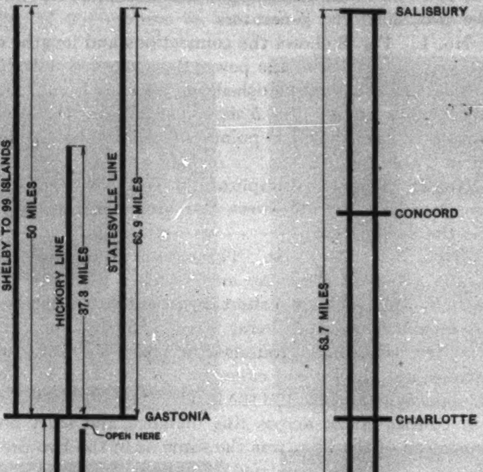

SHELBY TO 99 ISLANDS
50 MILES
HICKORY LINE
37.3 MILES
STATESVILLE LINE
63.9 MILES
SALISBURY
CONCORD
63.7 MILES
CHARLOTTE
GASTONIA
OPEN HERE
26.1 MILES
TEST INSULATOR
CATAWBA
SW.
GROUNDING SWITCH
33.3 MILES
GREAT FALLS POWER STATION

FIG. 4.—Connection diagram, tests 4 and 5

Vibrator No. 2 (the middle record) was connected to a current transformer in the grounding switch circuit.

Vibrator No. 3 (the bottom record) was connected to the current transformer in the ground circuit of the test insulator.

Source of Power. In all tests power was supplied from Great Falls by two, 3000-kw. generators.

Test No. 1. Fig. 3 shows the connections and lengths of the lines. The total length of the power lines was 144 miles (231.7 km.). The arc was extinguished at once and without disturbance to the system. Fig. 5 shows the arc over the insulator. A summary of the principal points shown by the oscillogram is given in Table No. 1.

Test No. 2. This was a duplicate of Test No. 1 and showed the same results. Fig. 6 shows the arc over the insulator. Fig. 9 is the oscillogram.

Tests Nos. 3 *A*, *B*, *C*, *D*. These tests were made to determine the action of the relay and switches when the ground was due to an arc over such a short distance that the line voltage could re-establish it after being extinguished. For this the No. 00 copper wire which grounded the pin of the test insulator was bent up, so that its end came within about an inch of the No. 00 copper wire attached to the head. The voltage to ground could, of course, spark across this distance and start an arc. The connection of the lines was the same as in the two previous tests, Fig. 2. This test was tried four times, with the following results: The arc started and the grounding switch closed. This extinguished the arc, and the switch at once opened. But before the switch was fully open, the arc started a second time. This brought the second stroke lock-device into operation, and the switch closed a second time and stayed closed. This permanently put out the arc, but, of course, left the system grounded.

Test No. 4. Fig. 4 shows the connections and lengths of the lines. The total length of the lines was 428 miles (669 km.). This was the entire system, with the exception of one section, 17 miles (27 km.) long. The arc was rather heavy, but was at once extinguished, and without disturbance to the system. Fig. 7 shows the arc over the insulator. Fig. 10 is the oscillogram.

Test No. 5. This was a duplicate of Test No. 4, and gave the same results. Fig. 8 shows the arc over the insulator. In all these pictures of the arc, the exposure was 0.04 second, and therefore the arc is probably shown during several cycles.

Effect of Arc on Insulator. The same insulator was used in all tests. It was absolutely uninjured. There was not even any chipping or cracking of the glaze, and no blemishes further than a little smoking.

It will be seen from the oscillograms that the time from the starting of the current in the switch to the extinguishing of

FIG. 5

FIG. 6

FIG. 7

FIG. 8

the arc is about two cycles. This is the time for the switch to move from the auxiliary contact to the main contact, during which time the oscillation damping resistance is in circuit.

TABLE NO. 1
ANALYSIS OF TESTS NUMBERS 1, 2, 4, 5

Test number.		1	2	4	5
Time for relay to close	Cycles	4.5	4.5	4.25	4.5
	Seconds	0.075	0.075	0.071	0.075
Time for switch to close	Cycles	24.5	22.5	24.0	21.5
	Seconds	0.408	0.374	0.401	0.358
Time arc is on	Cycles	29.0	27.0	28.25	26.0
	Seconds	0.483	0.449	0.472	0.433
Average current in arc, amps.	Maximum	70.	76.	247.	247.
	Effective	50.	54.	175.	175.
Average current in switch, amps.	Maximum	63.	76.	240.	240.
	Effective	45.	54.	170.	170.

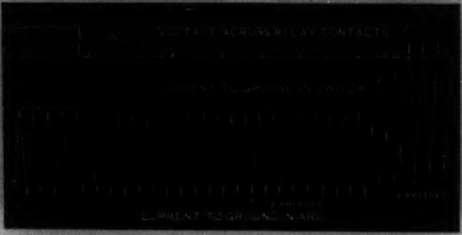


FIG. 9

The effective currents given in the table have been calculated from the maximum values on the assumption of a sine-wave form. Fig. 11 is a high-speed oscillogram from a later test

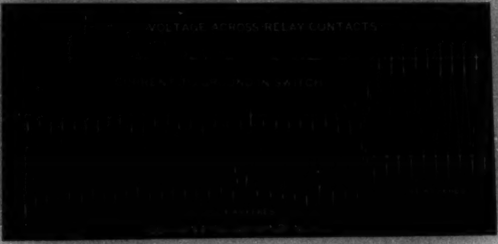


FIG. 10

which shows the wave shape of the current in the arc. This wave has a very pronounced third harmonic. An approximate analysis, gave as its equation, taking unity as the maximum value of the fundamental.

$$I = 1.000 \sin (\theta + 2.5°) - 0.201 \sin (3\,\theta + 11.5°) - 0.048 \sin 5\,\theta$$

This wave is so much peaked that the ratio of the effective to the maximum value is much lower than for a sine wave. It was not possible to make sufficient tests to determine whether the wave distortion was the same in all cases, and therefore, no correction of the current values for the wave shape has been attempted. But it seems probable that the actual effective values are slightly lower than those given in the table.

FIG. 11

Summary of Tests. An examination of these tests shows:

1. The current in both the arc and the grounding switch depends upon the extent of the lines on the system. This is to be expected, as these currents are flowing into a capacity, this capacity being proportional to the length of the lines.

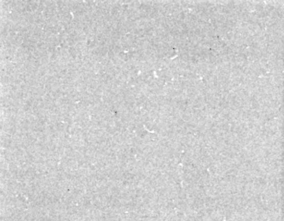
2. The arc is extinguished in a time not exceeding one-half second from the time of starting.

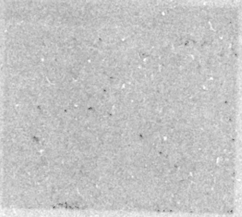
3. The insulator being uninjured, shows that even the very heavy arcs produced when the entire system is on will not injure the insulator when extinguished in one-half second.

4. When the arc is extinguished in such a short time, there is no disturbance on the lines or interruption of service either from the arc, or the operation of the grounding switch.

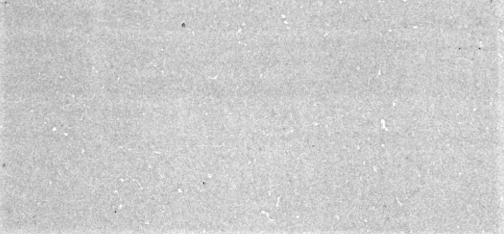
[illegible]

[illegible]





[illegible]



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A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

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TESTS OF LOSSES ON HIGH TENSION LINES

BY G. FACCIOLI

It is generally admitted that corona losses constitute the most serious objection to the use of higher voltages in transmission lines. For this reason a number of physicists and engineers have devoted and are devoting their attention to the study of corona phenomena. Their investigations can be divided into two classes.

First: Investigations in laboratories, where conductors of limited length and apparatus of comparatively small size are experimented upon.

Second: Investigations on high-tension lines under operating conditions or on experimental lines.

Since the opportunities for investigations of the latter category are limited, it seems advisable that the results of such experiments—though they may be incomplete—be gradually collected, until sufficient data are secured to warrant the deduction of reliable conclusions.

As a contribution to such a collection, this paper gives the results of tests taken on the lines of the Central Colorado Power Company. An investigation was undertaken on this power system to study line oscillations and switching phenomena and this will form the subject of a future paper. However, while the main investigation was in process, some tests on line losses were performed which, owing to the peculiar topographical conditions of this system, will prove of practical interest.

Fig. 1 is a map of the system.

The main Power House is located at Shoshone.

The three conductors of the three phase line are situated on a horizontal plane, with a distance of 124 in. (3.14 m.) between centers of adjacent conductors.

Each conductor between Shoshone and Denver consists of a hemp center, six-strand, copper cable, No. 0 B. & S. gauge, with the exception of a section between Leadville and Dillon where the conductors are of smaller size. From Denver to Boulder three, six-strand copper cables, No. 1 B. & S. are used.

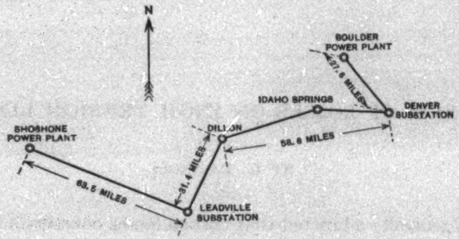

N
BOULDER
POWER PLANT
27.6 MILES
IDAHO SPRINGS
DENVER
SUBSTATION
SHOSHONE
POWER PLANT
DILLON
58.6 MILES
31.4 MILES
63.5 MILES
LEADVILLE
SUBSTATION

FIG. 1

As shown in Fig. 1, the length of the transmission line from Shoshone to Denver is 153.5 miles (247 km.) of which 63.5 miles (102 km.) are from Shoshone to Leadville, 31.4 miles (50 km.) from Leadville to Dillon and 58.6 miles (94 km.) from Dillon to Denver.

FIG. 2

The distance between Boulder and Denver is 27.6 miles (44 km.)

Power is delivered to Denver from Shoshone and Boulder, but at the time of the tests the Shoshone power house only was in operation. Fig. 2 shows the towers of the system. The insulators are all of the suspension type and have four insulating disks each.

The altitude and the climatic conditions of the country traversed by the transmission line are unusual. The line crosses the continental divide at three points, one between Shoshone and Leadville at an altitude of 12,000 ft. (3,657 m.), another between Leadville and Dillon at 12,500 ft. (3,810 m.), and the third between Dillon and Denver (Argentine Pass) at 13,700 ft. (4,175 m.). These exceptional conditions magnify the importance of the problem of line losses, as it is well known that the atmospheric losses increase with the altitude.

The 153.5 miles (247 km.) of line (from Shoshone to Denver) were energized from Shoshone as shown in Fig. 3. The line was entirely unloaded, no apparatus being connected to it with the exception, of course, of the generating system at Shoshone.

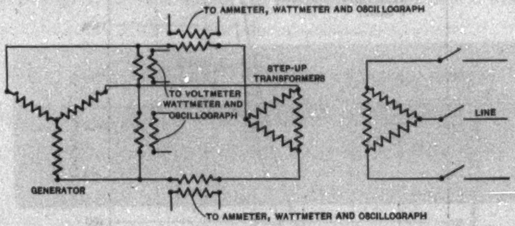

TO AMMETER, WATTMETER AND OSCILLOGRAPH
STEP-UP TRANSFORMERS
TO VOLTMETER WATTMETER AND OSCILLOGRAPH
LINE
GENERATOR
TO AMMETER, WATTMETER AND OSCILLOGRAPH

FIG. 3

This consisted of a 5,000-kw., 4000-volt, 60-cycle, three-phase alternator, connected to the low-tension side of three 3,333-kw. transformers, whose ratio of transformation was 4200 to 100,000 volts.

The generator windings were Y-connected, the three transformers being delta-connected on both primary and secondary sides.

Fig. 4 gives the kilowatt losses of this three-phase line(153.5 miles long) in function of the voltage between conductors at the power house.

The voltage was varied by regulating the excitation of the alternator and the measurements were taken on the low-tension side of the step-up transformers as follows: First, the transformers alone were connected to the generator, and the transformer losses recorded at a certain voltage; Second, the line was connected to the high-tension terminals of the transformers and the loss measured at the same low-tension voltage.

The difference between the two readings gave the total line losses, *i.e.*, the sum of ohmic, corona and insulator losses. This simple method of measurement is subject to criticism, but it was followed as the only one available, as there was neither time nor opportunity to procure special apparatus or to provide elaborate arrangements.

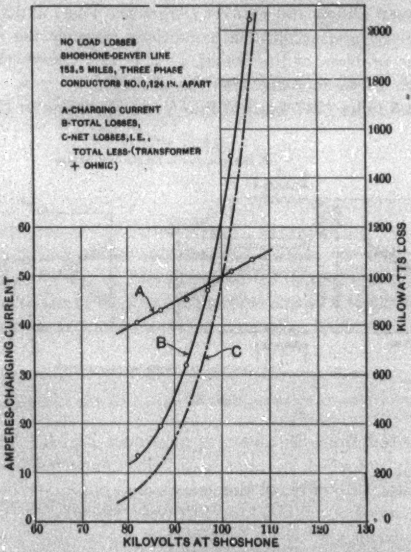


FIG. 4

As Fig. 3 shows, the currents were measured through a series transformer. This introduces an error into the measurements of the kilowatts, which amounts to 1.5 per cent at 100 kilovolts. Oscillograms of the e.m.f's. and currents were taken, and practically sine waves were obtained in every case. The waves of the generator e.m.f. were identical whether the transformers only were excited, or both the transformers and line were energized, and therefore the results may be considered accurate enough to substantiate the conclusions which follow and which are more qualitative than quantitative.

It must also be noted that since the low-tension side of the transformer was delta-connected, the triple frequency component of the exciting current was circulating in the delta and did not affect the ammeter readings and oscillograms of current.

Fig. 5 gives the e.m.f. and current energizing the Shoshone-Denver three-phase line. The record is taken at the generator end of the line at Shoshone according to the connections shown in Fig. 3. The voltage corresponds to 91.5 kilovolts between line conductors, and the current is 1080 amperes flowing in the generator windings.

In Fig. 4, curve *A* shows the charging current of the line and curve *B* gives the total losses measured at different voltages, that is to say, the line losses plus the transformer losses. Curve *C* gives the corona and insulator losses, *i.e.*, the losses remaining after the ohmic and the transformer losses have been subtracted from the total measured losses.

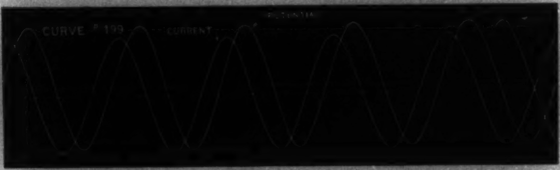


FIG. 5

The following table gives an idea of the relative importance of the transformer losses and line losses.

Kilovolts at Shoshone	Transformer losses	Corona and insulator losses
80	24	109
90	36	341
95	43	598
100	52	1003
105	64	1623

At 100 kilovolts, which is about the operating voltage of the system, the line losses under these conditions are 1000 kilowatts. Thus the operation of this system at 100 kilovolts would appear impracticable. However, when the system is loaded and in normal operation the line losses fall to small values, well within the limits of economical operation. The explanation of this phenomenon is obvious.

When the line is unloaded the voltage, which is 100 kilovolts at Shoshone, increases along the line, until at the far end of the line, at Denver, it is more than 10 per cent higher than at Shoshone.

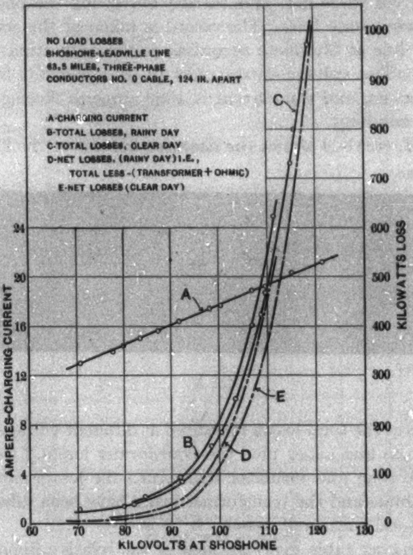


Fig. 6

The voltage at Denver could only be measured by connecting step-down transformers at Denver and measuring the potential on their low-tension side. Of course, the case of the open line is different as the exciting current of the step-down transformers, flowing through the line, modifies the conditions.

With two 2500-kw. transformers connected at Denver in open delta it was found that with 90 kilovolts at Shoshone the voltage at Denver was 100 kilovolts.

Hence the majority of the 1000 kw. measured when 100 kilovolts were held at Shoshone, were concentrated at the far end of the line, where the voltage was above 110 kilovolts.

As a proof of this the section of the line from Leadville to Denver was disconnected at Leadville and the three-phase losses of the section Shoshone-Leadville (63.5 miles, 102 km.) were measured, following the same method described above. Fig. 6 gives the results of these last measurements.

Curve *A* gives the charging current of the line.

Curve *B* the total losses (corona, ohmic, insulator and transformer losses) in rainy weather.

Curve *C* the total losses (corona, insulator, ohmic and transformer losses) in clear weather.

Curve *D* the corona and insulator losses deduced from curve *B*.

Curve *E* the corona and insulator losses deduced from curve *C*.

The following table deduced from curve *C* of Fig. 4 and curve *D* of Fig. 6 gives the losses of the line from Shoshone to Denver, the losses of the section from Shoshone to Leadville and the difference between the two values:

Kilovolts at Shoshone	Kilowatts Shoshone to Denver	Kilowatts Shoshone to Leadville	Difference
80	109	10.6	98.4
90	341	37.9	303.1
100	1003	152.	851

It follows that at 100 kilovolts held at Shoshone 63.5 miles (102 km.) of three-phase line give a loss of 150 kilowatts, but when 90 additional miles (27.4 km.) are connected at the end of this section, bringing the total length of line to 153.5 miles (247 km.), the losses become 1000 kw., *i.e.*, adding 90 miles (27.4 km.) of line introduces a loss of 850 kw.

The average atmospheric conditions for the tests of curve *B* Fig. 4 are

Barometric pressure	23.8	in. (604.5 mm.)
Temperature dry thermometer	51	deg. fahr.
Relative humidity	87	per cent

These measurements were taken at Shoshone and therefore they represent the atmospheric conditions at one point of the line only.

For curve *B* of Fig. 6 the atmospheric conditions were the same as before while for curve *C* Fig. 6 the conditions were

Barometric pressure	24 in. (609.5 mm.)
Temperature dry thermometer	55 deg. fahr.
Relative humidity	45.5 per cent

The difference between curve *B* and curve *C* is due to the fact that while curve *B* was taken in rainy weather the measurements of curve *C* were obtained in clear weather.

Although the Shoshone-Leadville tests were taken on a section of line 63.5 miles (102 km.) long, still the curves of Fig. 6 cannot be used to determine the critical voltage or the law which connects losses to kilovolts, because the voltage at the far end of the line is higher than the voltage at the power house and because of the different altitudes through which the transmission line runs. For this reason some experiments were conducted on the Denver-Boulder section of the system.

The distance between Denver and Boulder is 27.6 miles (44.4 km.) and the line runs at an average altitude of 5300 ft. (1615 m.) The conditions of the majority of the tests were as follows:

The main line from Shoshone to Denver was energized under normal conditions. The voltage at Denver was stepped down from 100,000 volts to 13,200 volts and power was delivered at this voltage to the 13,200-volt bus bars at Denver. The low-tension winding of a 2,500 kw., single-phase, step-up transformer was connected to these bus bars, and the high-tension winding energized two of the conductors of the three-phase line from Denver to Boulder. Different voltages were obtained by using different ratios of transformation or different combinations of step-down and step-up transformers. Fig. 7 is a sketch of the connections used.

The method of measurement was the same as the one employed at Shoshone, with the difference that the wattmeter was not used through a series transformer but its current coil was connected directly in the 13,200-volt circuit. This eliminates the error due to the phase displacement introduced by the current transformer. The potential coil of the wattmeter was, however, energized through a potential transformer.

Fig. 7 shows how the conductors of the Denver-Boulder line are transposed. In these tests two conductors only were energized, and the potential of the third conductor, measured by electrostatic voltmeter, was zero in every instance.

The measurements were taken for a period of two weeks during which the barometric pressure varied from a minimum of 24.1 in. (612 mm.) to a maximum of 24.7 in. (627 mm.); the temperature varied from 49 deg. to 74 deg. fahr. and the relative humidity from 21 to 35 per cent with an average of 29 per cent. These values were measured at Denver. It was found that readings taken on different days were not affected by humidity, for which, therefore, no correction was made. Also no correction was made for the slight difference in barometric pressure and temperature.

The results regarding humidity obtained in Colorado corroborate the tests taken in Pittsfield, where an apparatus, consisting of a rod parallel to a plate, was tested for corona during the period of a month. The voltage at which luminous corona appeared remained constant although the vapor product varied from 0.36 to 1 and the relative humidity from 43.5 per cent to 78 per cent. The barometric pressure varied between 28.7 in. (729 mm.) and 29.2 in. (742 mm.).

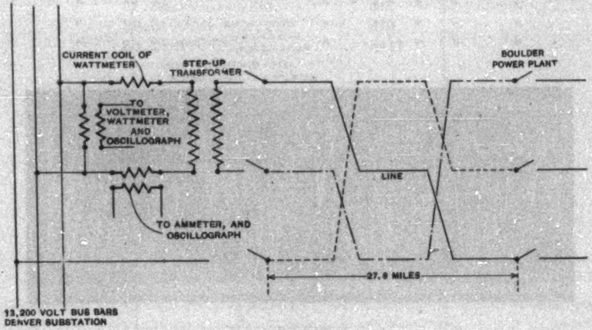

CURRENT COIL OF WATTMETER
STEP-UP TRANSFORMER
BOULDER POWER PLANT
TO VOLTMETER, WATTMETER AND OSCILLOGRAPH
LINE
TO AMMETER, AND OSCILLOGRAPH
27.8 MILES
13,200 VOLT BUS BARS DENVER SUBSTATION

FIG. 7

The Pittsfield tests prove that vapor product has no influence on the visual critical voltage of corona and in the Colorado tests no influence of the vapor product on line losses could be detected. This last point, however, cannot be definitely settled without further investigation in different seasons of the year and under more widely varying climatic conditions.

Oscillograms of e.m.f. and current were taken at different voltages and it was found that the shape of the wave of the e.m.f. remained constant throughout the tests. Fig. 8 is a representative oscillogram, and gives the voltage applied to the low-tension side of the transformer which energized the line, and the current flowing through the low-tension side of the transformer. This current was taken through a current transformer, and is the algebraic sum of the charging current of the single-phase line at 87 kilovolts and of the exciting current of the step-up transformer at the same voltage. The current is 31.53 amperes. The analysis of the current wave gives the following results:

Effective value of fundamental	25.5	amperes
" " " 3rd harmonic	11.0	"
" " " 5th "	6.14	"
" " " 7th "	13.15	"
" " " 9th "	0.93	"
" " " 11th "	2.63	"

Fig. 8

The third harmonic is introduced by the magnetization of the transformer, and the fifth and the seventh are emphasized by line capacity.

The curve of Fig. 9 gives the losses of 27.6 miles (44.4 km.) of single phase line (see Fig. 7), the conductors being No. 1 B. & S. copper cable, 124 in. (3.14 m.) apart for two-thirds of the distance and 248 in. (6.28 m.) for the remainder of the distance. Transformer and ohmic losses were subtracted from the total readings and the ordinates of the curve are the corona losses of the two conductors plus insulator losses.

An attempt was made to separate insulator losses from corona losses but the insulator losses (which were measured in dry weather only) were so small that no definite measurement of their value could be obtained, and they are neglected in the following discussion.

The voltage at the Boulder end of the line was measured by connecting a step-down transformer at Boulder and reading the voltage on the low tension side of this transformer. The voltage at Boulder resulted 2 per cent higher than at Denver.

Since the power factor of the readings was very low it was considered advisable to raise this power factor by using an artificial load (a water box) in multiple with the low-tension winding of the step-up transformer which energized the line. The measurements were taken as follows:

The transformer only was connected to the system and readings taken, then the line was connected to the transformer and readings taken at the same voltages as before. The difference between the kilowatts in the two cases gives the total losses of the line. Additional measurements were made, first, with the transformer and auxiliary load; second, with the transformer, auxiliary load and line. The utmost care was taken to keep the auxiliary load constant during these two sets of measurements. The introduction of the auxiliary load proved unnecessary as the results obtained with and without the extra load were the same.

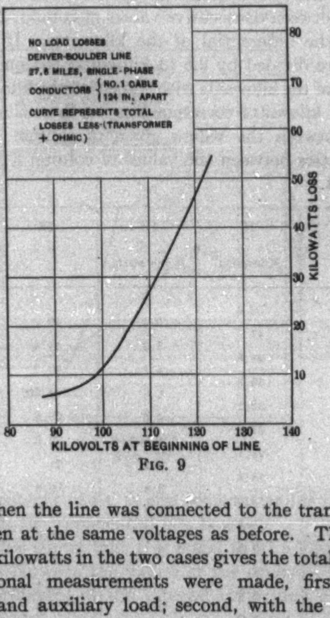


FIG. 9

In order to find an equation representing the curve of losses the following method was adopted. The points of the curve were plotted on logarithmic paper, using the logarithms of the kilowatts in function of the logarithms of the kilovolts, and the logarithms of the kilowatts in function of the kilovolts. The results were not satisfactory. Then the curve was differentiated, in order to obtain a preliminary idea of its form.

In the following table the first column gives the value of the kilovolts (abscissæ) taken at a constant interval of 2.5 kilovolts; the second column gives the kilowatts (ordinates) corresponding to the kilovolts of column 1. Column 3 (Δ kilowatts) gives the difference between consecutive values of column 2 and therefore represents the differential of the kilowatts. If the values of column 3 are divided by 2.5 (Δ kilovolts) the quotients are the derivatives of the kilowatts with respect to the kilovolts. Column 4 gives the kilowatts corresponding to the values of kilovolts mid-way between the values given in column 1. Column 5 gives the ratios between the values of column 3 and the values of column 4.

I Kilovolts	II Kilowatts	III Δ kilowatts	IV	V $\frac{\Delta \text{ kilowatts}}{\text{Kilowatts}}$
122.5	52.4			
		5.4	49.7	0.1085
120	47			
		5.2	44.4	0.117
117.5	41.8			
		5.1	39.3	0.127
115.	36.9			
		4.8	34.45	0.139
112.5	32.1			
		4.6	29.8	0.15
110	27.5			
		4.4	25.3	0.174
107.5	23.1			
		4.3	21	0.204
105	18.8			
		3.8	16.8	0. 26
102.5	15.			
		3.3	13.2	0.25
100	11.7			
		2.2	10.6	0.208
97.5	9.5			
		1.5	8.7	0.175
95.	8			
		1.2	7.4	0.162
92.5	6.8			
		0.6	6.6	
90	6.2			
		0.6	5.9	
87.5	5.6			
		0.6	5.3	
85	5.			

In curve *A* Fig. 10 are plotted the values of column 3. At 107.5 kilovolts, the curve of the differentials changes sharply its direction and form. Above 107.5 kilovolts curve *A* is a straight line, hence the law giving the kilowatts in function of the kilovolts (above 107.5 kilovolts) is represented by a quadratic equation. Below 107.5 kilovolts curve *A* is identical in form to the integral curve of Fig. 9, showing that the law giving the kilowatts in function of the kilovolts below 107.5 kilovolts is represented by an exponential equation.

Between 97.5 and 107.5 kilovolts, we may assume that the values of column 5 are constant and equal to the average value 0.222.

The exponential equation is of the general type kw. = $Ae^{B\,(\text{kv.}-C)}$ where e is the base of the Naperian logarithms, *A* and *B* are constants and *C* is also constant and is the critical voltage at which the exponential law begins.

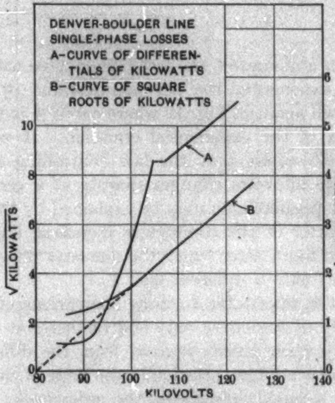


Fig. 10

The above table shows that *C* is equal to 97.5 kilovolts.

B is the ratio between the values of the derivatives and the values of the ordinates of the integral curve and is equal to

$$\frac{0.222}{2.5} = 0.089.$$

A represents the losses at the critical voltage (97.5 kilovolts) *i.e.*, 9.5 kilowatts.

We conclude that between 97.5 and 107.5 kilovolts the exponential law which gives the kilowatt losses in function of the kilovolts is kw. $= 9.5e^{0.089\,(\text{kv.} - 97.5)}$. The following table gives the values of the losses calculated with the above equation and the values of the kilowatts deduced from the curve of Fig. 9.

Kilovolts	Calculated kilowatts	Tested kilowatts
110	28.8	27.5
107.5	23.1	23.1
105	18.5	18.8
102.5	14.8	15
100	11.84	11.7
97.5	9.5	9.5
95	7.61	8
90	4.89	6.2

As had been anticipated, the test points agree with the points given by the exponential law between 97.5 and 107.5 kilovolts.

This is shown again in Fig. 11 where curve *A* is the graphical representation of the exponential equation. It would not be unreasonable to admit that the law controlling the losses in function of the kilovolts changes sharply at a certain definite point, and the phenomenon may be explained by the hypothesis that the diameter of the conductors increases, due to corona, up to a certain limit, after which the diameter remains constant and the losses follow a different law.

However, it is impossible to draw conclusions of this nature from the study of one curve only and furthermore it is not advisable to rely upon results derived from the differential of a function, because a large variation in the slope of the curve may correspond to a small variation in the ordinates of the integral curve.

Now, curve *A* of Fig. 10 is a straight line above 107.5 kilovolts and from the constants of this straight line it is possible to derive the quadratic law which gives kilowatts in function of kilovolts. But on account of the uncertainty regarding derivatives of functions, as explained above, a different method was used. This method consists in plotting the square root of the kilowatts in function of the kilovolts. Curve *B* of Fig. 10 was thus obtained.

The upper part of this curve is a straight line down to a point corresponding to 97.5 kilovolts and it is remarkable that this is the same voltage at which the exponential law starts. The quadratic law has the general form kilowatts = D (kilovolts $-$ E)^2, in which E is the voltage at which the upper straight line of curve B, Fig. 10, cuts the axis of abscissæ, namely, 80 kilovolts. D is readily figured from any point of the loss curve and the equation becomes kilowatts = 0.0306 (kilovolts $-$ 80)^2. This equation is represented graphically in curve B of Fig. 11. The tested points check fairly well with the quadratic law above 97.5 kilovolts and the exponential law appears unnecessary.

These results show the necessity of a clear understanding as to the method of determining the so-called " critical voltage ".

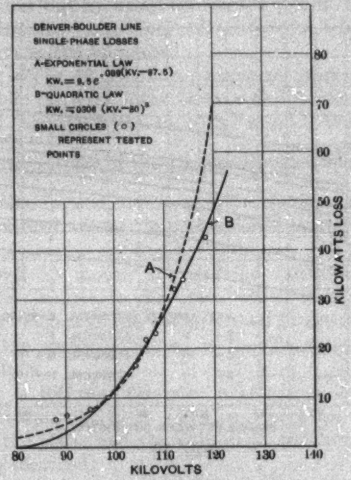


FIG. 11

In this case 97.5 kilovolts is a " critical voltage " because above this point the curve of losses follows a definite law different from the law followed below this point; 80 kilovolts is also a " critical voltage " as shown by the quadratic equation.

These voltages are different from the critical voltage which would be obtained by following Mershon's method, according to which no definite law is applied in determining the point at which the lower and upper limb of the curve meet. Following Mershon's method we should judge that the critical voltage in this case is 92.5 kilovolts.

It appears that 80 kilovolts is in this case the most definite voltage which can be called " critical " and if the results of other experiments will confirm this conclusion it is advisable to call " critical voltage " the voltage at which loss, as given by the quadratic equation, begins.

An attempt was made to find the critical voltage which should be expected in this case using the data published by Mershon in the TRANSACTIONS of the A. I. E. E., 1908. Fig. 39 of Mershon's paper shows the relation between the critical voltage and the distance between conductors, for different sizes of conductors.

The law generally accepted to give the critical voltage at which

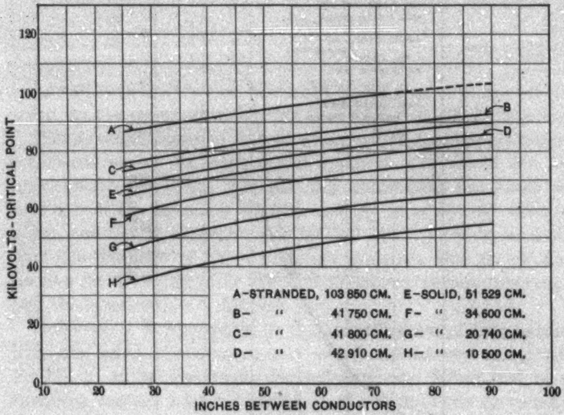


FIG. 12

corona appears in function of the diameter of the conductors and the distance between conductors is $V = M\,r \log \frac{D}{r}$, where M is a constant depending upon the barometric pressure and temperature, D is the distance between the centers of the conductors, r the radius of the conductor. A glance at the curves of Fig. 12 (which are a reproduction of the curves of Fig. 39 of Mershon's paper) shows that the above law does not hold in this case. In fact, the increase in critical voltage due to an increase in spacing of the conductors is constant, and therefore independent of the radius of the conductor.

For solid conductors the curves of Fig. 12 are represented by the equation $V = 36.7 \log_{10} D - 700\, d \log_{10} d - 90$, where D is the distance between conductors in inches and d is the diameter of the conductors in inches. This is a rather surprising result as the theoretical equation may be written as follows:

$$V = M\, d \log D - N\, d \log d + P$$

M, N and P being constants. With the exception of the first term this theoretical equation agrees with the equation representing the curves of Fig. 12.

The constants in the case of stranded conductors have not been worked out but by using the curves of Fig. 12 and interpolating we find that the critical voltage for No. 1 B. & S. cables (124 in. apart) is 106 kilovolts.

The curves of Fig. 12 refer to a barometric pressure of 29.5 in. (750 mm.) while the tests of the Denver-Boulder line were taken at an average pressure of 24.6 in. (614.7 mm.). We should then expect a critical voltage of the Denver-Boulder line of $106 \dfrac{24.6}{29.5}$ = 88.5 kilovolts, instead of 92.5 as given by the curve of Fig. 9.

That the critical voltage is proportional to the atmospheric pressure is generally admitted. However, the opportunity presented itself to repeat at Leadville (altitude 10,500 ft., 3,200 m.) some simple corona tests, which were performed a year before at Pittsfield and are described in the paper by Mr. Moody and the writer published in the TRANSACTIONS of the A. I. E. E., 1909.

Brass rods of different diameter were suspended parallel to a plate at a distance of 12 in. (30.4 cm.) between the center of the rod and the plate, and the voltage at which visible corona appeared was recorded.

Utmost care was taken to reproduce in Leadville the identical conditions under which the tests were taken at Pittsfield, and oscillograms of the e.m.fs. in both cases gave sine waves. The following table gives the results obtained at Pittsfield and Leadville and the ratios between the two critical voltages.

Diameter of rod	Kilovolts at Pittsfield	Kilovolts at Leadville	Ratio
⅛ in.	38	29.6	1.28
¼ "	57	45	1.27
⅜ "	75	57.2	1.31
½ "	90.7	66.6	1.36

The barometric pressure was 29 in. (736 mm.) at Pittsfield and 20.2 in. (513 mm.) at Leadville. The temperature was 59 deg. fahr. at Leadville and 80 deg. fahr. at Pittsfield.

The correction coefficient suggested by Ryan is $\frac{b}{459+t}$ where b is the barometric pressure in inches and t is the temperature in degrees fahr. Using the values of pressure and temperature corresponding to the tests at Leadville and Pittsfield, Ryan's formula gives as ratio between the two critical voltages 1.38. The complication introduced in the measurements by the temperature makes it impossible to reach any conclusion as to the exact influence of altitude.

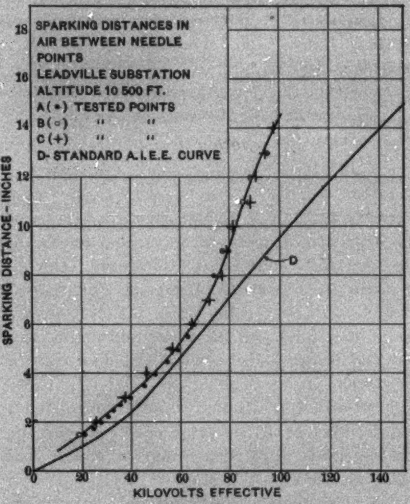


FIG. 13

Some spark tests were also taken at Leadville and the results are plotted in Fig. 13. These tests were taken between sharp needle points, and the A. I. E. E. rule of keeping a distance twice the length of the gap between the gap itself and the nearest object, was strictly observed. The experiments were performed in the Leadville substation of the Central Colorado Power Company at an altitude of 10,500 ft. (3,200 m.). In Fig. 13 are plotted the original points taken on three different days. The tests *A* were taken under the following atmospheric conditions:

Barometric pressure	20.2 in. (513 mm.)
Temperature	64.5 deg. fahr.
Relative humidity	22.5 per cent

For the tests *B*

Barometric pressure	20.14 in. (510.5 mm.)
Temperature	56.5 deg. fahr.
Relative humidity	45.5 per cent

and for the test *C*

Barometric pressure	20.15 in. (512 mm.)
Temperature	65.5 deg. fahr.
Relative humidity	43 per cent

In Fig. 13 the standard curve of the A. I. E. E. is plotted so that the two curves may be compared.

Some three-phase tests were also taken on the Denver-Boulder section but they could be performed at one voltage only.

At 84.5 kilovolts between conductors the corona and insulator losses of the three-phase line were 20.7 kw. It is interesting to compare this value of the three-phase losses with the value of the single-phase losses at the same voltage to ground. The voltage to ground is 49 kilovolts and the single-phase losses for 98 kilovolts between conductors are 10.5 kw. For the same voltage to ground, the three-phase losses are then practically double the single phase losses, but it must be remembered that the three-phase losses were measured on 27.6 miles (44.4 km.) of line as represented in Fig. 3, while the single-phase line experimented upon consisted of two conductors 124 in. (3.14 m.) apart for a distance of 18.4 miles (29.6 km.) and 248 in. (6.28 m.) apart for the remaining 9.2 miles (14.8 km.).

The high corona losses shown by these tests are of theoretical interest only, as they do not affect the economical operation of the system. However, this investigation although limited and incomplete, points to the danger of corona losses assuming prohibitive values should any greatly increased operating voltages be attempted. Therefore, in addition to the further investigation necessary to establish the law for losses on transmission lines and for the critical voltage of corona, it would appear that there is a field for considerable thought and experiment along the line of developing some efficient means of limiting the losses to permissible values.

DISCUSSION ON "DESIGN, CONSTRUCTION AND TESTS OF AN ARTIFICIAL TRANSMISSION LINE", "PROTECTION OF ELECTRICAL TRANSMISSION LINES", "TESTS OF ARCING GROUND SUPPRESSORS ON THE 40,000-VOLT SYSTEM OF THE SOUTHERN POWER CO.," "TESTS OF LOSSES ON HIGH TENSION LINES." SCHENECTADY, FEBRUARY 15, 1911.

Ralph D. Mershon: There are one or two questions I would like to ask. One is with reference to the method of measurement of the line voltage which assumed the constancy of the ratio of the step-up power transformer. I wonder how accurate it was. A small error in voltage in some of the measurements would make a considerable amount of difference in the loss curves, and there is a chance for distortion of wave, other modifications of voltage, due to reactions in the transformer, producing a change of ratio.

Another statement appears which raises a somewhat similar question as to the wave form impressed on the line, and the possibility there was for distortion. This, of course, is a question similar to the previous one in regard to measurement. In the case of Fig. 4, it would be interesting to know where the charging current to the line was measured. I do not see that there is any statement made as to whether it was made on the low voltage side of the transformer or in the line itself. The average atmospheric conditions of the tests of curve *B* Fig. 4 of the other curves are given. It would have been an addition to the paper, I think, if the individual readings for some of the points on the curves were given. Additional information bearing on this matter has been given me by Mr. Faccioli as applied to Fig. 9. He says that the vapor product applying to that curve varied from 0.11 to 0.274. It is brought out in my Niagara paper that for low value of vapor product the variation in the losses with vapor product are not considerable, not such as would ordinarily attract attention, and it was because of that, I think, that I did not notice them at all in my Telluride measurements. It is only when you get above these values, as I remember it in the neighborhood of 0.3 and 0.4, that the effect of the moisture in the atmosphere becomes marked.

This low value of the vapor product might or might not account for lack of variation in visible corona with variation of atmospheric conditions. It would seem from the tests made so far by Mr. Faccioli that possibly the visible corona is not affected by humidity conditions but as I think I have said once or twice before, the critical point as I define it, is not the point at which corona begins, but at which the loss curve turns sharply upward.

Mr. Faccioli has determined that according to my Niagara data, the critical voltage of the Denver-Boulder line, should be 88.5 kilovolts. Unfortunately, Fig. 9 has not a sufficient amount of the lower part of the curve for the accurate application of my method. But my estimate for that curve, such as there is of it, is that by my method the critical voltage would be about 87 kilovolts, which is not so far out from the value Mr. Faccioli obtains. The curve of Fig. 9 is the result of differences of two sets of measurements. The subtraction method may lead to errors of considerable magnitude especially in the lower part of the curve, resulting in considerable variation in the curve one way or the other. I think it hardly fair, therefore, to give this curve much weight in any critical discussion of either my method of obtaining the critical point or my results.

There is another question I would ask in regard to where the wattmeter was used with the coil directly in the high voltage circuit. What was the possibility of electrostatic effects affecting its reading?

The method of analysis Mr. Faccioli has adopted for determining the critical point does not appeal to me much. You first get a set of observations in which there is more or less error. You draw in the most probable curve. Then you get an empiric formula for the top part of the curve as closely as you can; more or less error there. Then by means of this formula you extend the upper limb of the curve down to the voltage axis, find the intersection and call that the critical point. It seems to me my method is much quicker, safer and much more rational especially as I do not agree in the use of the square law for the upper part of the curve. Although the square law may appear to apply, it seems to me there is every reason why it actually should not apply. For, if we are dealing with a sine wave voltage the loss above the critical point should be some function of that part of the area of the wave included between the two values of critical voltage. Therefore this loss cannot, rationally, follow the simple law of squares. As a matter of fact, if you derive the expression for the effective voltage of that part of the sine wave included between the two values of critical voltage, assume it to be acting against the critical and through a resistance and derive a curve connecting total impressed voltage and loss, you get a curve which has a shape closely approximating that of the actual loss curves obtained.

Mr. Faccioli says: "The law which gives the critical voltage at which corona appears in function of the diameter of the conductors and the distance between conductors is $V = M\,r \log D/r$, where M is a constant depending upon the barometric pressure and temperature, D is the distance between the centers of the conductors, r the radius of the conductor." I thought that expression was the expression giving the rate of fall of potential at the surface of the conductor, and that Professor Ryan had demonstrated pretty thoroughly that that was not the law which governed the beginning of corona, and that that is the reason why these curves do not follow the theoretical law as pointed out by Mr. Faccioli. They do, however, follow the empirical formula which I gave in my paper which is not, however, independent of diameter.

This question of the vapor product and its effect is something I have been looking for very interestedly in the further measurements of others. So far no one else seems to have gotten it. Referring to Mr. Creighton's paper, I hope that Mr. L. C. Nicholson who is here will tell us about work he has been doing independently along the same lines, and some of the results he has obtained.

Charles S. Ruffner: The measured losses referred to in the paper occur when the receiving end of the line is open circuited, and are greatly reduced when the load is delivered, or even when unloaded substation transformers are connected. That these losses are not serious in service is shown by the meter readings for the year. During 1910 88.2 per cent of the number of kilowatt hours generated was delivered to the low tension side of the substation transformers; that is, 11.8 per cent of the energy generated was used in station auxiliaries or lost in step-up transformers, transmission line and substation transformers. It is probable that less than 6/10 of this total loss should be charged to the line, so that the loss, in line only, amounts to about 7 per cent of the energy generated.

On account of the difficulty of measuring the potential at the receiving end of the line at open circuit, the effective value and wave form of the voltage is unknown under these conditions, but it is probable that the effective voltage is 25 per cent higher than at the generating station. It is also probable that in the section of line farthest from the generating station the distortion of the voltage wave may greatly increase the losses during part of the cycle above the loss that would correspond to the same effective voltage with a sine wave. At least it is possible that over some intermediate section of the line where the effective value of the voltage is insufficient to produce excessive loss, there may still be parts of the distorted voltage wave sufficiently above this critical voltage to cause excessive losses during part of the cycle. This would give greater losses at any measured effective voltage than those calculated for sine waves.

An interesting point that cannot be determined from the data at hand is suggested by the distortion of the wave of charging current, which, under some conditions, may approximate triple frequency. This may have an appreciable effect on such losses as are connected with inductive effects. That is to say, there may be a question whether the calculated ohmic losses, which have been subtracted from the measured total open circuit loss, should not be modified because of the change in current distribution in the circuit caused by this higher frequency current. If there is any such effect, the resulting values of "corona and insulator losses" given by such subtraction might include other losses. However, the fact that the greatest losses occur in the parts of the line farthest from the generating station shows that the loss is almost altogether a function of the voltage.

It is unfortunate that there is not available an oscillogram of the voltage wave at the open end of the line when no transformers are connected. The importance of this is evident when, under normal voltages at Shoshone, the power required for the total line is about 2,300 kw. at open circuit and is reduced to about 1,300 kw. by connecting unloaded transformers to the line at Denver and at Boulder.

L. C. Nicholson: Professor Creighton mentions three foes to the continuity of service on a long distance transmission line; first, direct lightning stroke shattering insulators, second, induced effects from nearby lightning which may cause insulators to flashover, and third, outside interference. Mr. Mershon promises an insulator which will relish the direct stroke, and Professor Creighton tells us how to get rid of flashovers on one wire at a time so as to obviate consequent damage to insulators and conductors. No one is bold enough to suggest a cure for outside interference.

Professor Creighton explains why flashovers should occur on only one wire at a time. However, flashovers do not occur always as they should, and frequently involve two and sometimes three phases simultaneously. Our experience with these matters indicates that 60 per cent of all lightning disturbances are two-wire short circuits, that is, two insulators on different phases arc over simultaneously, 30 per cent are single insulator flashovers, that is, from one wire to ground, and 10 per cent are three-phase short circuits caused by simultaneous flashing of insulators on all three phases. Experience further indicates that the single-insulator flashovers involving limited current, usually go out after a few seconds, and do no considerable damage. Hence an arc suppressor to be of maximum benefit should provide for suppressing phase to phase arcs as well as phase to ground arcs.

Apparatus is in operation on the lines of the Niagara, Lockport & Ontario Power Co., to extinguish arcs occurring from line to ground and between phases and to accomplish this result in so short a time that synchronous receiving apparatus remains in step and thus avoid shutdowns. This apparatus consists essentially of enclosed fuses connected to the lines by means of quick acting air switches actuated by excess current in the line wires. The fuses act to shunt the primary short circuit on the lines and thus extinguish the arc. The switches are selective and short circuit by fuses the phase or phases which are already short circuited by the flashover arc or arcs. The fuses consist of No. 14 B. & S. copper wire contained in a paper tube 6 ft. long. The entire operation of throwing the fuses on the circuit and burning them out consumes less than 1/5 of a second. This short time is too small to throw heavily loaded synchronous motors or rotary convertors out of step. In fact the disturbance to the system is barely noticeable. Single-phase oil switches have been tried for this purpose, but we found them too slow to close and in great danger of exploding when opening heavy short circuit current, which amounts to 2,000 amperes or more.

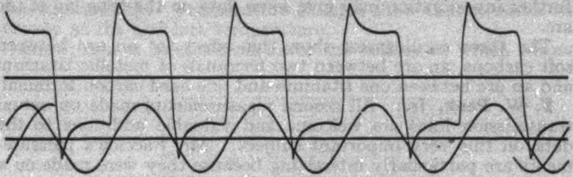
Taylor Reed: In the papers which have been presented this evening there has been quite a wide application of the oscillograph in the observations made, ranging all the way from comparatively laboratory conditions in Professor Cunningham's paper to quite trying, what you may call road conditions, in Mr. Faccioli's paper. I would like to speak more particularly with reference to the oscillograph observations in Mr. Faccioli's paper. The oscillograph is usually considered quite a delicate instrument, but I think it is used under conditions there which quite demonstrate its practicability. The particular instrument in use was not a new one by any means, it had seen some pretty severe service under factory conditions. It was taken out to quite a number of remote points, where the matter of accident was serious, and where the matter of repairs was very formidable. Where appliances were very meagre it was shipped about a number of times, half a dozen or more, from one point to another. It was used under all sorts of crude conditions and the films were developed under such circumstances and with such appliances as could be got together at the various points of observation. Further in some of the observations it was necessary, as I understand, to relay the signals for the switch operation through two or three persons at the observing end, through more than a hundred miles of private telephone line, and through two or three persons at the switch end, and yet the observations were obtained with an exposure of the film of only a very few seconds, two or three or four seconds. I may say that the instrument as sent out was not in all particulars adapted to the purpose—the observer put on it, with such appliances as he had available, the necessary additional apparatus, to use very much longer films than had been provided, etc., showing a capability and resourcefulness of the oscillograph operator in the matter of taking observations, of which we have had altogether too little. The oscillograph in its development was brought into actual practical use by practical necessities rather than for academic purposes, but when it was prepared, however, and offered for use, it was taken up and adopted more immediately in academic quarters than in practical operating quarters, after which followed its adoption quite extensively for more practical operating purposes, and it is now distributed fairly widely for these purposes. I am sorry to say that I think a good many of the pieces of apparatus turned out for academic purposes have gone into glass cases and for the most part reposed there for show purposes, and I think that those which have been applied to operating conditions have been much more satisfactorily used.

J. L. R. Hayden: In the latter part of Professor Creighton's paper two important and little understood phenomena are discussed, the time lag of the dielectric spark and the time lag of the arc.

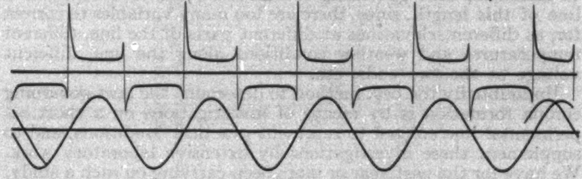
The industrial importance of the dielectric spark lag is obvious when seeing the enormous transient voltages which are required to break down even a short gap. Still less is known on the time lag of the arc. We have very complete data on the electrical characteristics of the arc under stationary conditions, largely from the work of Dr. Steinmetz, but very little on the transient phenomena of the arc.

Some years ago when developing the mercury arc rectifier we tried to find the time lag of the formation of the mercury arc by studying the time of overlap required for stability.

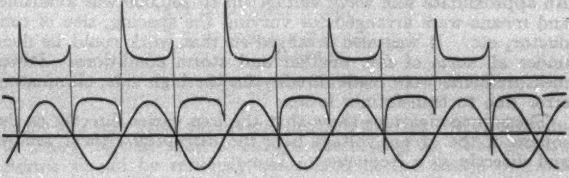
60 CYCLE ARC. 2 SOLID ½" SOFT ELECTRA CARBONS. 130.5 V. 3 A. 1.74 CM.



60 CYCLE ARC. ⅝" TIC; F-17 LOWER, 11/16" SOLID HARD CARBON UPPER. 3 A., .318 CM.



60 CYCLE ARC. ⅝" TIC; F-17 LOWER, F-17-5 UPPER ELECTRODE. 3 A. .603 CM.



In the mercury arc rectifier during every half wave the arc is formed by the dying out arc of the preceding half waves. By inductance the arcs are overlapped so as to maintain each arc until the next one is formed. By gradually reducing the inductance we tried to find the minimum overlap of the arc and from that the time required to start the arc. With currents of from 1 to 2 amperes and about 20 cm. arc length, this time was about one-thousandth of a second, but very much shorter with larger currents and shorter arcs. We found that even minute traces of residual gases in the vacuum greatly retarded the formation of the arc so that the above values can be considered only as the upper limit of time.

Recently we have tried to investigate the same phenomenon by studying alternating arcs by oscillograph.

In stationary conditions maximum current gives minimum voltage in the arc.

Oscillograms of alternating arcs show the minimum voltage to take place later than the maximum current, and from this further investigation may give some data on the time lag of the arc.

The three oscillograms show this effect for an arc between soft carbons, an arc between two terminals of metallic titanium and an arc between one titanium and one hard carbon terminal.

F. W. Peek, Jr.: All corona measurements made on actual transmission lines are welcome and valuable additions to the data on this very important subject. Mr. Faccioli's measurements are particularly interesting because they were made on a line operating right at the *critical voltage*. It is difficult, however, to formulate laws governing corona loss from tests made on a line of this length, since, there are too many variables to correct for, as different elevations at different parts of the line, different temperatures and weather conditions along the line, different voltage at the two ends, etc.

Undoubtedly the best method to determine the laws governing corona formation is by means of investigations on a short experimental line erected to represent practical conditions, and to supplement these investigations by extensive laboratory work. We have for the past year or more been carrying on such a study. An experimental line was erected representing standard practice. An approximate sine wave voltage up to 250,000 was available, and means were arranged for varying the spacing, size of conductor, etc. It was also arranged so that work could be done under all sorts of fair weather and storm conditions. Power measurements were made directly on the high side, eliminating error due to transformer losses.

These investigations show that the loss varies directly as the square of the excess voltage over the *disruptive critical voltage*, and directly as a frequency. Thus:

$$p = a f \, (e - e_0)^2 \qquad (1)$$

where p = kilowatt loss.
e = kilovolts line.
c is a term varying with the size of the wire and spacing.
f = frequency.

e_0 we have called the *disruptive critical voltage*. e_0 is much lower than the *visual critical voltage*, e_v, for small conductors and approaches e_v in value for large conductors.

Theoretically no loss should occur below the *visual critical voltage*, e_v loss does occur, however, due to irregularities, dirt, etc., on the surface of the wire. For line voltages near e_0, the loss is greater than given by equation (1) for large wire, and less for small wires. This small excess loss is due to " dirt " and is apparently represented by:

$$p_1 = g\, e^{-h\,(e_0-e)^2} \tag{2}$$

Curves taken over a very wide range show no change in e_0 due to humidity. Temperature changes show that e_0 varies inversely as the absolute temperature.

Snow, rain or sleet storms lower the voltage at which corona forms to a very great extent and increase the loss. Wet wires due to heavy fog also show a decided decrease in e_0. The effect of storms should be seriously considered in the design of transmission lines. Looking at Fig. 1: curve *A* shows the total measured loss during a snow storm, curve *B* shows the corresponding fair weather loss.

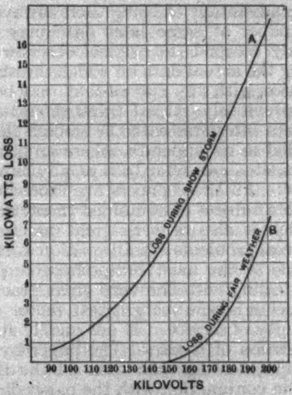


FIG. 1.—Corona loss

L. T. Robinson: With reference to the work these investigators have been able to do with the oscillograph, it seems to me that it is very unfortunate they have not been able to get better results, with what appears to me to be such a good tool; that is, I think it is extremely unfortunate that the apparent reproductions are not reproductions at all, but that they have been drawn, presumably with fidelity, but we do not know that they have. It has nearly always been possible to get—I believe we have been able to demonstrate this without question—a good clear, definite, original reproduction that carries all the original data with it, I would like to take what little time is at my disposal in this discussion, to protest against the use of redrawn oscillograph records where the originals can be used, which I believe is in almost every case, possible. If redrawing must be done, it should be done in a way so that it has no deception about it—that is, a black line on a white ground, showing that it is not an oscillograph record but something else. We would then avoid all complications, and if we saw one of these black lines on a white ground we would simply believe as much of it as we saw fit to. There are many points that may come up in checking records that are not of interest, perhaps, to the observer who makes the records at the time. If we reproduce the actual record it has the advantage of being there always, and some one who reads the paper at some later date may find something in it that entirely escaped the original observer. It is just the same as including the actual data on which the observations were based in connection with any curves that may be drawn—which was referred to previously—this I think should always be done. If the original data interferes with the smooth flow of the text it should be included in an appendix where any one who cares to verify the curves, etc., can refer to it at any time.

Chas. F. Scott: All these papers are exceedingly interesting as they deal with a subject of combined theoretical and research importance, which is also of very great practical importance. They attack the real problems in transmission work. Mr. Creighton's paper is one of the most comprehensive papers that has been presented dealing with the very great practical difficulties and problems in what is now the greatest factor in transmission work, the continuity of service. It not merely states a problem, but gives the solution of it also. The paper by Messrs. Burkholder and Marvin, dealing with tests on the Southern Power Company's line, in conjunction with the paper of Mr. Creighton, shows pretty conclusively the operation of this method under actual service conditions. We are fortunate to have presented from another source, a line of parallel work closely following the one explained by Mr. Creighton, which, as I understand, has been in use on the important and extensive lines of the Niagara, Lockport and Ontario Power Company. All this means progress, progress of the most substantial and best kind. It is the direct proof of what I was saying this afternoon as to the present attitude of the large manufacturing companies towards the practical operating problems. This is not directly a commercial problem of the manufacturing company, it is rather a problem dealing in the large and broad gauge way with the industry, by which electric service may be made more reliable, and after all it is the final object of all our work to give better service. The relation of the manufacturing company towards this work is not a narrow commercial one, the problems are studied in the broadest way, and time and ability and money are directed towards their solution. All those engaged in high tension work will be much profited by the papers which have been presented here at this session.

G. Faccioli: I will answer quickly some of Mr. Mershon's questions. The volts were measured on the secondary of the step-up transformer. The transformer was a 2,500-kw. transformer, and the voltage was measured on the secondary side. However, some of the tests were checked by using a spare 2,500 kw. transformer as a potential transformer connected across the high tension line, and measuring the electromotive force on the low tension side of the transformer. This is a method which has been advocated this afternoon. The charging current was measured on the low tension side. It is not exactly the charging current, but the difference between the charging current and the exciting current of the transformer.

I do not think any conclusion can be drawn from my paper on vapor product, because the measurements of the atmospheric conditions were taken at one point of the line only.

Mr. Mershon says that the lower part of the curve might be in error, and that the method of determining the critical voltage by the point where the two curves meet is uncertain.

The method which I propose, to determine the critical voltage does not consist in taking the point where the two limbs of the curve meet, but in observing the point where the curve, given by the quadratic law, cuts the axis of the abscisse. I believe this method of determining the critical voltage is much more accurate and positive. Furthermore, the lower part of the curve may be uncertain, but no attempt was made to find an equation for it. At 97.5 kilovolts, where the quadratic law begins, the line losses were so much higher than the transformer losses, that the results appear reliable. Regarding electrostatic effects in the wattmeter, the current coil was connected to the potential coil to eliminate such effects.

E. E. F. Creighton: Although we are really retracing the oscillograms, we find we can better reproduce them by tracing them. We try to do it faithfully, and if we do miss anything, it is better to have the loss than to have oscillograms which you cannot read at all. I think the better way would be to print the oscillograms black on white, and get better results. I think that is being considered now by publishers. I want to express my appreciation of the work done by Mr. Nicholson. He certainly has added much to the value of the work in transmission line protection.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

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MECHANICAL FORCES IN MAGNETIC FIELDS

BY CHARLES P. STEINMETZ

1. General

Mechanical forces appear wherever magnetic fields act on electric currents. The work done by all electric motors is the result of these forces. In electric generators, they oppose the driving power and thereby consume the power which finds its equivalent in the electric power output. The motions produced by the electromagnet are due to these forces. Between the primary and the secondary coils of the transformer, between conductor and return conductor of an electric circuit, etc., such mechanical forces appear.

The electromagnet, and all electrodynamic machinery, are based on the use of these mechanical forces between electric conductors and magnetic fields. So also is that type of transformer which transforms constant alternating voltage into constant alternating current. In most other cases however, these mechanical forces are not used, and therefore are commonly neglected in the design of the apparatus, under the assumption that the construction used to withstand the ordinary mechanical strains to which the apparatus may be exposed, is sufficiently strong to withstand the magnetic mechanical forces. In the large apparatus, operating in the modern huge electric generating systems, these mechanical forces due to magnetic fields may however, especially under abnormal, though not infrequently occurring conditions of operation (as short circuits), assume such formidable values, so far beyond the normal mechanical strains, as to require consideration. Thus large transformers on big generating systems have been torn to pieces by the magnetic mechanical forces of short circuits, cables have been torn from their supports, disconnecting switches blown open, etc.

In the following, a general study of these forces will be given. This also gives a more rational and thereby more accurate design of the electromagnet, and permits the determination of what may be called the efficiency of an electromagnet.

Investigations and calculations dealing with one form of energy only, as electromagnetic energy, or mechanical energy, usually are relatively simple and can be carried out with very high accuracy. Difficulties however arise when the calculation involves the relation between several different forms of energy, as electric energy and mechanical energy. While the elementary relations between different forms of energy are relatively simple, the calculation involving a transformation from one form of energy to another, usually becomes so complex, that it either can not be carried out at all, or even only approximate calculation becomes rather laborious and at the same time gives only a low degree of accuracy. In most calculations involving the transformation between different forms of energy, therefore it is preferable not to consider the relations between the different forms of energy at all, but to use the *law of conservation of energy* to relate the different forms of energy, which are involved.

Thus, when mechanical motions are produced by the action of a magnetic field on an electric circuit, energy is consumed in the electric circuit, by an induced e.m.f. At the same time, the stored magnetic energy of the system may change. By the law of conservation of energy, we have

Electric energy consumed by the induced e.m.f. = mechanical energy produced, + increase of the stored magnetic energy. (1)

The consumed electric energy, and the stored magnetic energy, are easily calculated, as their calculation involves one form of energy only, and this calculation then gives the mechanical work done, $= F\,l$, where F = mechanical force, and l = distance over which this force moves.

Where mechanical work is not required, but merely the mechanical forces, which exist, as where the system is supported against motions by the mechanical forces—as primary and secondary coils of a transformer, or cable and return cable of a circuit—the same method of calculation can be employed, by assuming some distance l of the motion (or dl); calculating the mechanical energy $w_0 = F\,l$ by (1), and therefrom the mechanical force as $F = \frac{w_0}{l}$, or $F = \frac{d w_0}{d l}$.

Since the induced e.m.f., which consumes (or produces) the electric energy, and also the stored magnetic energy, depend on the current and the inductance of the electric circuit, and in alternating-current circuits the impressed voltage also depends on the inductance of the circuit, the inductance can frequently be expressed by supply voltage and current; and by substituting this in equation (1), the mechanical work of the magnetic forces can thus be expressed, in alternating-current apparatus, by supply voltage and current.

In this manner, it becomes possible for instance to express the mechanical work and thereby the pull of an alternating electromagnet, by simple expressions of voltage and current, or to give the mechanical strains occurring in a transformer under short circuits, by an expression containing only the terminal voltage, the short-circuit current, and the distance between primary and secondary coils, without entering into the details of the construction of the apparatus.

This general method, based on the law of conservation of energy, will be illustrated by some examples, and the general equations then given.

2. The Constant Current Electromagnet

Such magnets are, for instance, the series operating magnets of constant current arc lamps on direct-current and alternating-current circuits.

Let i_0 = current, which is constant during the motion of the armature of the electromagnet, from its initial position 1, to its final position 2, l = the length of this motion, or the stroke of the electromagnet, in cm., and n = number of turns of the magnet winding.

The magnetic flux Φ, and the inductance

$$L = \frac{n\,\Phi}{i_0}\,10^{8} \tag{2}$$

of the magnet, vary during the motion of its armature, from a minimum value,

$$\Phi_1 = \frac{i_0\,L_1}{n}\,10_8 \tag{3}$$

in the initial position, to a maximum value,

$$\Phi_2 = \frac{i_0 \; L_2}{n} 10^8 \tag{4}$$

in the end position of the armature.

Hereby an e.m.f. is induced in the magnet winding,

$$e' = n \frac{d\,\Phi}{d\,t} 10^{-8} = i_0 \frac{d\,L}{d\,t} \tag{5}$$

This consumes the power

$$p = i_0\, e' = i_0^2 \frac{d\,L}{d\,t} \tag{6}$$

and thereby the energy

$$w = \int_1^2 p\, d\, t = n\, i_0^2 \,(L_2 - L_1) \tag{7}$$

Assuming that the inductance, in any fixed position of the armature, does not vary with the current, that is, that magnetic saturation is absent,* the stored magnetic energy is:

In the initial position, 1,

$$w_1 = \frac{i_0^2\, L_1}{2} \tag{8}$$

in the end position, 2,

$$w_2 = \frac{i_0^2\, L_2}{2} \tag{9}$$

The increase of the stored magnetic energy, during the motion of the armature, thus is

$$w' = w_2 - w_1 = \frac{i_0^2}{2} \,(L_2 - L_1) \tag{10}$$

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* If magnetic saturation is reached, the stored magnetic energy is taken from the magnetization curve, as the area between this curve and the vertical axis.

The mechanical work done by the electromagnet thus is, by the law of conservation of energy,

$$w_0 = w - w'$$

$$= \frac{i_0^2}{2}(L_2 - L_1) \text{ joules.} \qquad (11)$$

If l = length of stroke, in cm., F = average force, or pull of the magnet, in grammes weight, the mechanical work is

$$F\,l \text{ g-cm.}$$

Since

$$g = 981 \text{ cm-sec.} \qquad (12)$$

= acceleration of gravity, the mechanical work is, in absolute units,

$$F\,l\,g$$

and since one joule = 10^7 absolute units, the mechanical work is

$$w_0 = F\,l\,g\,10^{+7} \text{ joules.} \qquad (13)$$

From (11) and (12) then follows:

$$F\,l = \frac{i_0^2}{2\,g}\,(L_2 - L_1)\,10^{+7} \text{ g-cm.} \qquad (14)$$

as the *mechanical work of the electromagnet*, and:

$$F = \frac{i_0^2}{2\,g}\;\frac{L_2 - L_1}{l}\,10^7 \text{ g.} \qquad (15)$$

as the average force, or pull of the electromagnet, during its stroke l.

Or, if we consider only a motion element $d\,l$;

$$F = \frac{i_0^2}{2\,g}\;\frac{d\,L}{d\,l}\,10^{+7} \text{ g.} \qquad (16)$$

as the force, or pull of the electromagnet in any position l.

Reducing from g-cm. to ft-lb., that is, giving the stroke l in feet, the pull F in pounds, we divide by

$$454 \times 30.5 = 13{,}850$$

which gives, after substituting for g from (**12**):

$$(\mathbf{14}):\ F\,l = 3.68\, i_0^2\,(L_2 - L_1) \text{ ft.-lb.} \qquad (\mathbf{17})$$

$$(\mathbf{15}):\ F = 3.68\, i_0^2\,\frac{L_2 - L_1}{l} \text{ lb.} \qquad (\mathbf{18})$$

$$(\mathbf{16}):\ F = 3.68\, i_0^2\,\frac{d\,L}{d\,l} \text{ lb.} \qquad (\mathbf{19})$$

These equations apply to the direct-current electromagnet as well as to the alternating-current electromagnet.

In the alternating-current electromagnet, if i_0 is the effective value of the current, F is the effective or average value of the pull, and the pull or force of the electromagnet pulsates with double frequency between 0 and $2\,F$.

In the alternating-current electromagnet usually the voltage consumed by the resistance of the winding, $i_0\,r$, can be neglected compared with the voltage consumed by the reactance of the winding, $i_0\,x$, and the latter, therefore, is practically equal to the terminal voltage e of the electromagnet. We have then, by the general equation of self-induction,

$$e = 2\,\pi\,f\,L\,i_0 \qquad (\mathbf{20})$$

where f = frequency, in cycles per second.

From which follows,

$$i_0\,L = \frac{e}{2\,\pi\,f} \qquad (\mathbf{21})$$

and substituting (**21**) in equations (**14**) to (**19**), gives as the equation of the *mechanical work, and the pull of the alternating-current electromagnet.*

In the metric system;

$$F\,l = \frac{i_0\,(e_2 - e_1)\,10^7}{4\,\pi\,f\,g} \text{ g-cm.} \qquad (\mathbf{22})$$

$$F = \frac{i_0\,(e_2 - e_1)\,10^7}{4\,\pi\,f\,g\,l} = \frac{i_0}{4\,\pi\,f\,g}\ \frac{d\,e}{d\,l}\,10^7 \text{ g.} \qquad (\mathbf{23})$$

In foot pounds;

$$F\,l = \frac{.586\, i_0\,(e_2 - e_1)}{f} \text{ ft-lb.} \tag{24}$$

$$F = \frac{.586\, i_0\,(e_2 - e_1)}{f\,l} = \frac{.586 i_0}{f} \quad \frac{d\,e}{d\,l} \text{ lb.} \tag{25}$$

Example.—In a 60-cycle alternating-current lamp magnet, the stroke is 3 cm., the voltage, consumed at the constant alternating current of 3 amperes, is 8 volts in the initial position, 17 volts in the end position. What is the average pull of the magnet?

$$l = 3 \text{ cm.}$$

$$e_1 = 8$$

$$e_2 = 17$$

$$f = 60$$

$$i_0 = 3$$

Hence, by **(23)**:

$$F = 122 \text{ g. } (= 0.27 \text{ lb.})$$

The work done by an electromagnet, and thus its pull, depend, by equation **(22)**, on the current i_0 and the difference in voltage between the initial and the end position of the armature, $e_2 - e_1$; that is, depend upon the difference in the volt-amperes consumed by the electromagnet at the beginning and at the end of the stroke. With a given maximum volt-amperes, $i_0\,e_2$, available for the electromagnet, the maximum work would thus be done, that is, the greatest pull produced, if the volt-amperes at the beginning of the stroke were zero, that is, $e_1 = 0$, and the theoretical maximum output of the magnet thus would be

$$F_m\,l = \frac{i_0\,e_2\,10^7}{4\,\pi\,f\,g} \tag{26}$$

and the ratio of the actual output, to the theoretically maximum output, or the efficiency of the electromagnet, thus is, by (**22**) and (**26**),

$$\eta = \frac{F}{F_m} = \frac{e_2 - e_1}{e_2} \tag{27}$$

or, using the more general equation (**14**), which also applies to the direct current electromagnet;

$$\eta = \frac{L_2 - L_1}{L_2} \tag{28}$$

The efficiency of the electromagnet, therefore, is the difference between maximum and minimum voltage, divided by the maximum voltage; or the difference between maximum and minimum volt-ampere consumption, divided by the maximum volt-ampere consumption; or the difference between maximum and minimum inductance, divided by the maximum inductance.

As seen, this expression of efficiency is of the same form as that of the thermodynamic engine;

$$\frac{T_2 - T_1}{T_2}$$

From (**26**) it also follows, that the maximum work which can be derived from a given expenditure of volt-amperes, $i_0\, e_2$, is limited. For $i_0\, e_2 = 1$, that is, for one volt-ampere, the maximum work, which could be derived from an alternating electromagnet, is, from (**26**):

$$F_m\, l = \frac{10^7}{4\,\pi\, f\, g} = \frac{810}{f} \text{ g-cm.} \tag{29}$$

That is, a 60-cycle electromagnet can never give more than 13.5 g-cm., and a 25-cycle electromagnet never more than 32.4 g-cm. pull per volt-ampere supplied to its terminals.

Or inversely, for an average pull of one g. over a distance of one cm., a minimum of $\frac{1}{13.5}$ volt-ampere is required at 60 cycles, and a minimum of $\frac{1}{32.4}$ volt-ampere at 25 cycles.

Or, reduced to pounds and inches:

For an average pull of one lb. over a distance of one in., at least 86 volt-amperes are required at 60 cycles, and at least 36 volt-amperes at 25 cycles.

This gives a criterion by which to judge the success of the design of electromagnets.

3. THE CONSTANT POTENTIAL ALTERNATING ELECTROMAGNET

If a constant alternating potential e_0 is impressed upon an electromagnet, and the voltage consumed by the resistance, $i\,r$, can be neglected, the voltage consumed by the reactance x is constant and is the terminal voltage e_0, thus the magnetic flux ϕ also is constant during the motion of the armature of the electromagnet. The current i however varies, and decreases from a maximum i_1 in the initial position, to a minimum i_2 in the end position of the armature, while the inductance increases from L_1 to L_2.

The voltage induced in the electric circuit by the motion of the armature,

$$e' = n \frac{d\,\phi}{d\,t} 10^{-8} \tag{30}$$

then is zero, and therefore also the electrical energy expended;

$$w = 0$$

That is, the electric circuit does no work, but the mechanical work of moving the armature is done by the stored magnetic energy.

The increase of the stored magnetic energy is

$$w' = \frac{i_2^2 L_2 - i_1^2 L_1}{2} \tag{31}$$

and since the mechanical energy, in joules, is by (**13**),

$$w_0 = F\,l\,g\,10^{-7}$$

the equation of the law of conservation of energy,

$$w = w' + w_0 \tag{32}$$

then becomes

$$0 = \frac{i_2^2 L_2 - i_1^2 L_1}{2} + F l g \, 10^{-7}$$

or

$$F l = \frac{i_1^2 L_1 - i_2^2 L_2}{2 g} \, 10^7 \text{ g-cm.} \qquad \textbf{(33)}$$

Since, from the equation of self-induction, in the initial position;

$$e_0 = 2 \pi f L_1 i_1 \qquad \textbf{(34)}$$

in the end position;

$$e_0 = 2 \pi f L_2 i_2 \qquad \textbf{(35)}$$

substituting (**34**) and (**35**) in (**33**), gives the equation of the constant potential alternating electromagnet.

$$F l = \frac{e_0 (i_1 - i_2)}{4 \pi f g} \, 10^7 \text{ g-cm.} \qquad \textbf{(36)}$$

and

$$F = \frac{e_0 (i_1 - i_2)}{4 \pi f g l} \, 10^7 = \frac{e_0}{4 \pi f g} \; \frac{d i}{d l} \, 10^7 \text{ g.} \qquad \textbf{(37)}$$

or, in ft-lb.

$$F l = \frac{.586 \, e_0 (i_1 - i_2)}{f} \text{ ft-lb.} \qquad \textbf{(38)}$$

$$F = \frac{.586 \, e_0 (i_1 - i_2)}{f l} = \frac{.586 \, e_0}{f} \; \frac{d i}{d l} \text{ lb.} \qquad \textbf{(39)}$$

Substituting $Q = e i$ = volt-amperes, in equations (**36**) to (**39**) of the constant potential alternating electromagnet, and equations (**22**) to (**25**) of the constant-current alternating magnet, gives the same expression of mechanical work and pull:

In metric system,

$$F\,l = \frac{\Delta\,Q}{4\,\pi\,f\,g}\,10^7 \text{ g-cm.} \tag{40}$$

$$F = \frac{\Delta\,Q}{4\,\pi\,f\,g\,l}\,10^7 = \frac{1}{4\,\pi\,f\,g}\;\frac{d\,Q}{d\,l}\,10^7 \text{ g.} \tag{41}$$

In foot-pounds,

$$F\,l = \frac{.586\;\Delta\,Q}{f} \text{ ft-lb.} \tag{42}$$

$$F = \frac{.586\;\Delta\,Q}{f\,l} = \frac{.586}{f}\;\frac{d\,Q}{d\,l} \text{ lb.} \tag{43}$$

where $\Delta\,Q$ = difference in volt-amperes consumed by the magnet in the initial position, and in the end position of the armature.

Both types of alternating current magnet then give the same expression of efficiency;

$$\eta = \frac{\Delta\,Q}{Q_m} \tag{44}$$

where Q_m is the maximum volt-amperes consumed, corresponding to the end position in the constant current magnet, to the initial position in the constant potential magnet.

4. SHORT CIRCUIT STRESSES IN ALTERNATING CURRENT TRANSFORMERS

At short circuit, no magnetic flux passes through the secondary coils of the transformer, if we neglect the small voltage consumed by the ohmic resistance of the secondary coils. If the supply system is sufficiently large to maintain constant voltage at the primary terminals of the transformer even at short circuit, full magnetic flux passes through the primary coils.* In this case the total magnetic flux passes between primary coils and secondary coils, as self-inductive or leakage flux. If then x = self-inductive or leakage reactance, e_0 = impressed e.m.f., $i_0 = \frac{e_0}{x}$ is the short circuit current of the transformer. Or, if as usual the reactance is given in per cent, that is, the $i x$ (where i = full load current of the transformer) given in per cent of e, the short circuit current is equal to the full load current divided by the percentage reactance. Thus a transformer with 4 per cent reactance would give a short circuit current, at maintained supply voltage, of 25 times full load current.

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* If the terminal voltage drops at short circuit on the transformer secondaries, the magnetic flux through the transformer primaries drops in the same proportion, and the mechanical forces in the transformer drop with the square of the primary terminal voltage, and with a great drop of the terminal voltage, as occurs for instance with large transformers at the end of a transmission line or long feeders, the mechanical forces may drop to a small fraction of the value, which they have on a system of practically unlimited power.

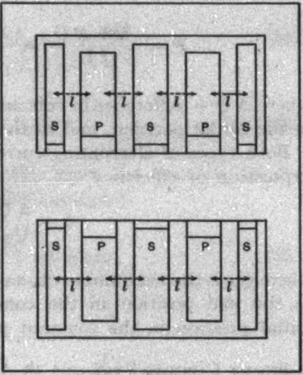


FIG. 1

To calculate the force F, exerted by this magnetic leakage flux on the transformer coils — (which is repulsion, since primary and secondary currents flow in opposite direction) we may assume, at constant short-circuit current i_0, the secondary coils moved against this force F, and until their magnetic centers coincide with those of the primary coils; that is, by the distance l, as shown diagrammatically in Fig. 1, the section of a shell type transformer. When brought to coincidence, no magnetic flux passes between primary and secondary coils, and during this motion, of length l, the primary coils thus have cut the total magnetic flux ϕ of the transformer.

Hereby in the primary coils a voltage has been induced,

$$e' = n \frac{d\,\Phi}{d\,t} 10^{-8}$$

where n = effective number of primary turns.

The work done or rather absorbed by this voltage e', at current i_0, is

$$w = \int e'\, i_0\, d\,t = n\, i_0\, \Phi\, 10^{-8} \text{ joules.} \tag{45}$$

If L = leakage inductance of the transformer, at short circuit, where the entire flux Φ is leakage flux, we have,

$$\Phi = \frac{L\, i_0}{n}\, 10^8 \qquad (46)$$

hence, substituted in (45)

$$w = i_0^2\, L \qquad (47)$$

The stored magnetic energy at short circuit is

$$w_1 = \frac{i_0^2\, L}{2} \qquad (48)$$

and since at the end of the assumed motion through distance l, the leakage flux has vanished by coincidence between primary and secondary coils, its stored magnetic energy also has vanished, and the change of stored magnetic energy therefore is

$$w' = w_1 = \frac{i_0^2\, L}{2} \qquad (49)$$

Hence the mechanical work of the magnetic forces of the short circuit current is

$$w_0 = w - w' = \frac{i_0^2\, L}{2} \qquad (50)$$

It is, however, if F is the force, in g., l the distance between the magnetic centers of primary and secondary coils:

$$w_0 = F\, l\, g\, 10^{-7} \text{ joules.}$$

Hence

$$F\, l = \frac{i_0^2\, L}{2\, g}\, 10^7 \text{ g-cm.} \qquad (51)$$

and

$$F = \frac{i_0^2\, L}{2\, g\, l}\, 10^7 \text{ g.} \qquad (52)$$

the mechanical force existing between primary and secondary coils of a transformer at the short circuit current i_0.

Since at short circuit, the total supply voltage e_0 is consumed by the leakage inductance of the transformer, we have

$$e_0 = 2 \pi f L i_0 \tag{53}$$

hence, substituting (**53**) in (**52**), gives

$$F = \frac{e_0 i_0 10^7}{4 \pi f g l} \text{ g.}$$

$$= \frac{810 e_0 i_0}{f l} \text{ g.} \tag{54}$$

Example.—Let, in a 25-cycle 1667-kw. transformer, the supply voltage $e_0 = 5200$, the reactance = 4 per cent. The transformer contains two primary coils between three secondary coils, and the distance between the magnetic centers of the adjacent coils or half coils is 12 cm., as shown diagrammatically in Fig. 1. What force is exerted on each coil-face during short circuit, in a system which is so large as to maintain constant terminal voltage?

At 5200 volts and 1667 kw., the full load current is 320 amperes. At 4 per cent reactance the short-circuit current therefore $i_0 = \frac{320}{.04} = 8000$ amperes. Equation (**54**) then gives, for $f = 25$, $l = 12$;

$$F = 112 \times 10^6 \text{ g.}$$

$$= 112 \text{ tons.}$$

This force is exerted between the four faces of the two primary coils, and the corresponding faces of the secondary coils, and on every coil face thus is exerted the force

$$\frac{F}{4} = 28 \text{ tons.}$$

This is the average force, and the force varies with double frequency, between 0 and 56 tons, and is thus an enormous force.

Substituting $i_0 = \frac{e_0}{x}$ in (**54**), gives as the short-circuit force of an alternating current transformer, at maintained terminal voltage e_0, the value

$$F = \frac{e_0^2\, 10^7}{4\, \pi\, f\, g\, l} = \frac{810\ e_0^2}{f\, l}\ \mathrm{g}.$$

That is, the short circuit stresses are inversely proportional to the leakage reactance of the transformer.

In large transformers on systems of very large power, safety therefore requires the use of as high reactance as possible.

5. Repulsion between Conductor and Return Conductor

If i_0 is the current flowing in a circuit consisting of a conductor and the return conductor parallel thereto, and l the distance between the conductors, the two conductors repel each other by the mechanical force exerted by the magnetic field of the circuit, on the current in the conductor.

As this case corresponds to that considered in section 2, equation (**16**) applies, that is;

$$F = \frac{i_0^2}{2\, g}\, \frac{d\, L}{d\, l}\, 10^7\ \mathrm{g}. \tag{16}$$

The inductance of two parallel conductors, at distance l from each other, and conductor diameter l_d, is, per cm. length of conductor;

$$L = \left(4 \log \frac{2\, l}{l_d} + \mu\right) 10^{-9}\ \mathrm{h}. \tag{55}$$

Hence, differentiated;

$$\frac{d\, L}{d\, l} = \frac{4 \times 10^{-9}}{l}$$

and, substituted in (**16**);

$$F = \frac{i_0^2}{50\, g\, l}\ \mathrm{g}. \tag{56}$$

or substituting (12);

$$F = \frac{20.4\, i_0^2\, 10^{-8}}{l} \text{ g.} \tag{57}$$

If $l = 150$ cm. (5 ft.)

$$i_0 = 200 \text{ amperes.}$$

this gives

$F = 0.0054$ g. per cm. length of circuit, hence it is inappreciable.

If however the conductors are close together, and the current very large, as the momentary short circuit current of a large alternator, the forces may become appreciable.

For example, a 2200-volt 4000-kw. quarter-phase alternator feeds through single conductor cables having a distance of 15 cm. (6 in.) from each other. A short circuit occurs in the cables, and the momentary short-circuit current is 12 times full-load current. What is the repulsion between the cables?

Full load current is, per phase, 910 amperes. Hence, short-circuit current, $i_0 = 12 \times 910 = 10{,}900$ amperes. $l = 15$. Hence,

$$F = 160 \text{ g. per cm.}$$

Or, multiplied by $\frac{30.5}{454}$

$$F = 10.8 \text{ lb. per ft. of cable.}$$

That is, pulsating between 0 and 21.6 lb. per ft. of cable. Hence sufficient to lift the cable from its supports and throw it aside.

In the same manner, similar problems, as the opening of disconnecting switches under short circuit, etc., can be investigated.

6. GENERAL EQUATIONS OF MECHANICAL FORCES IN MAGNETIC FIELDS

In general, in an electromagnetic system in which mechanical motions occur, the inductance L is a function of the position l during the motion. If the system contains magnetic material, in general the inductance L also is a function of the current i, especially if saturation is reached in the magnetic material.

Let, then, L = inductance, as function of current i and position l.

L_1 = inductance, as function of the current i, in the initial position 1 of the system.

L_2 = inductance, as function of the current i, in the end position 2 of the system.

If then Φ = magnetic flux, n = number of turns interlinked with the flux, the induced e.m.f. is

$$e' = n \frac{d\,\Phi}{d\,t} 10^{-8} \tag{58}$$

We have, however,

$$n\,\Phi = i\,L\,10^{8}$$

hence,

$$e' = \frac{d\,(i\,L)}{d\,t} \tag{59}$$

the power of this induced e.m.f. is

$$p = i\,e' = i\,\frac{d\,(i\,L)}{d\,t}$$

and the energy

$$w = \int_1^2 p\;d\;t = \int_1^2 i\,d\,(\,i\,L)$$

$$= \int_1^2 i^2\;d\;L + \int_1^2 i\,L\,d\,i \tag{60}$$

The stored magnetic energy in the initial position 1 is

$$w_1 = \int_0^1 i\,d\,(i\,L_1) \tag{61}$$

In the end position 2,

$$w_2 = \int_0^2 i\,d\,(i\,L_2) \tag{62}$$

and the mechanical work thus is, by the law of conservation of energy

$$w_0 = w - w_2 + w_1$$

$$= \int_1^2 i\, d\, (i L) + \int_0^1 i\, d\, (i L_1) - \int_0^2 i\, d\, (i L_2) \qquad \textbf{(63)}$$

and since the mechanical work is

$$w_0 = F\, l\, g\, 10^{-7} \qquad \textbf{(64)}$$

We have;

$$F\, l = \frac{10^7}{g} \left\{ \int_1^2 i\, d\, (i L) + \int_0^1 i\, d\, (i L_1) - \int_0^2 i\, d\, (i L_2) \right\} \text{ g-cm.} \qquad \textbf{(65)}$$

If L is not a function of the current i, but only of the position, that is, if saturation is absent, L_1 and L_2 are constant, and equation (**65**) becomes,

$$F\, l = \frac{10^7}{g} \left\{ \int_1^2 i\, d\, (i L) + \frac{i_1^2 L_1 - i_2^2 L_2}{2} \right\} \text{ g-cm.} \qquad \textbf{(66)}$$

a. If i = constant, equation (**66**) becomes:

$$F\, l = \frac{10^7}{g} \; \frac{i^2 (L_2 - L_1)}{2}$$

(Constant-current electromagnet)

b. If L = constant, equation (**66**) becomes:

$$F\, l = 0.$$

That is, mechanical forces are exerted only where the inductance of the circuit changes with the mechanical motion which would be produced by these forces.

c. If $i L$ = constant, equation (**66**) becomes:

$$F l = \frac{10^7}{g} \frac{i L (i_1 - i_2)}{2}$$

(Constant-potential electromagnet.)

In the general case, the evaluation of equation (**66**) can usually be made graphically, from the two curves, which give the variation of L_1 with i in the initial position, of L_2 with i in the final position, and the curve giving the variation of L and i with the motion from the initial to the final position.

In alternating magnetic systems, these three curves can be determined experimentally by measuring the volts as function of the amperes, in the fixed initial and end position, and by measuring volts and amperes, as function of the intermediary positions, that is, by strictly electrical measurement.

As seen, however, the problem is not entirely determined by the two end positions, but the function by which i and L are related to each other in the intermediate positions, must also be given. That is, in the general case, the mechanical work and thus the average mechanical force, are not determined by the end positions of the electromagnetic system. This again shows an analogy to thermodynamic relations.

DISCUSSION ON "MECHANICAL FORCES IN MAGNETIC FIELDS", PITTSFIELD, FEBRUARY 15, 1911.

A. S. McAllister: The author has called attention to the error involved in dividing the difference in energies in two positions of a solenoid plunger by the distance it moved to determine the force acting upon the solenoid. He has also intimated, without stating directly, the cause for that error. The energy in the magnetic field is expressed as $\frac{1}{2} L I^2$. It is somewhat analagous, not to potential energy, but to kinetic energy, that is, not to $f\,l$, but to $\frac{1}{2} M V^2$. In dealing with potential energies, the energy in one position may be subtracted from the energy in another position, and the difference divided by the distance between the two positions then gives the force. However, in the case of the solenoid the two energies are the kinetic energy under one condition and the kinetic energy under another condition, and the movement of the plunger is merely an incident to the change in the condition. The energy in the magnetic field cannot be defined as $\frac{1}{2} L I^2$ unless L is constant, as is true for the air circuit, but is not true for the iron circuit. Therefore, the equation given by Dr. Steinmetz cannot be applied directly when iron is in the circuit; which means that the equations, if used, become very complicated. As a matter of fact it is preferable not to use the equation, but as the author indicates, resort to graphical or similar methods for determining the energies in the two positions or the change in the energy with the change in position.

G. Faccioli: The value of mechanical forces which act on transformers under short circuit conditions is enormous, as pointed out by Dr. Steinmetz. So the transformer which has enjoyed the reputation of having no movable parts presents to the designer a difficult problem, that is the problem of keeping the windings in place when a short circuit occurs.

This purpose may be accomplished by adopting for the windings an exceptionally strong mechanical structure and, in certain instances, by distributing uniformly the leakage flux through the width of the leakage path thereby distributing the mechanical forces evenly throughout the leakage area.

But on account of the magnitude of these forces it seems necessary to improve the conditions by reducing as much as possible the forces themselves.

These forces are proportional to the leakage flux and to the current.

The leakage flux is proportional to the applied e.m.f. and if we assume that the power behind a transformer is unlimited and therefore the voltage will be maintained at its full value under all conditions, it is impossible to reduce the value of the leakage flux. We can, however, reduce the current by increasing the reactance of the transformer.

For instance, if a transformer has two per cent reactance, this means that two per cent of the full voltage will send full load current through the apparatus with its secondary short circuited. If we apply full voltage to the transformer 50 times full load current will flow.

We then have, for two per cent reactance, flux one, short circuit current fifty, force fifty times one equals fifty.

If we double the reactance and make it four per cent, then the short circuit current at full voltage is twenty-five times full load current or one-half the value with two per cent reactance. The flux is one as before, the short circuit current is 25, therefore the force is 25 times one equals 25 or one-half what it was in the preceding case.

By increasing the reactance of a transformer we decrease in inverse proportion the mechanical forces on the windings.

If the reactance is not all in the transformer as inherent reactance but is divided in two parts, one inherent in the transformer and the other external to the transformer, the conditions are somewhat different.

Let us assume two per cent reactance in the transformer and two per cent outside reactance, then the total reactance of the circuit is four per cent and the short circuit current is 25 times normal load current. This short circuit current flowing through the external reactance causes a drop of e.m.f. equal to two per cent times 25, equals fifty per cent normal electromotive force.

It follows that we apply to the transformer one-half only of the total voltage and that the leakage flux is reduced to one-half its full value. The force is then equal to one-half times 25 equals 12½ as against 25 which was the value of the force when the four per cent reactance was all inherent reactance of the transformer.

It appears that by judicious use of reactance we may be able to improve short circuit conditions and to reduce the mechanical forces to a considerable extent.

Formerly in the days of small units and limited power the factor which controlled the amount of reactance in the transformer was the regulation. Now, with large units and enormous powers, another point of view is added, and that is the ability of a transformer to withstand short circuit.

As it is generally the case the design of the transformer must be a compromise, because while on one hand we should use low reactance to secure good regulation, on the other hand we need high reactance to limit the value of the short circuit current.

In large power transformers the ability to withstand short circuits is far more important to modern engineers than good regulation.

Cassius M. Davis: I wish to offer an explanation of the operation of a solenoid when used to actuate an oil switch by means of a toggle mechanism. The plunger of the solenoid acts on the middle joint of the toggle, moving it until the two arms are brought a little beyond the point where they are in the same straight line.

The electrical operation may be outlined by reference to Fig. 1. The plunger in its initial position gives the solenoid the inductance L_1, and the current, starting at time t_0, would rise along the transient curve i_1. After time t_1 the current has risen to produce sufficient flux to start the plunger and it begins to close the toggle. In doing so the inductance of the solenoid increases, and an increase of inductance means a decrease in the rate at which the current rises in the solenoid. Thus at t_1 the current begins to rise along another transient curve indicated by i_2. At t_2 the arms of the toggle have come into line which suddenly releases the load and the joint breaks back to lock the switch mechanism; the plunger then suddenly jumps to its final position reaching it at t_3, and with it the inductance increases from L_2 to L_3, which may mean an actual decrease of current, indicated by i_3. From t_3 the current rises along a curve i_4 determined by L_3 and the current at time t_3.

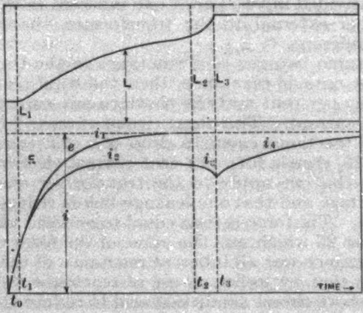


FIG. 1

The power at any instant is the product of the current and the induced voltage at that instant, and the induced voltage is proportional to the ordinates, e, above the curve; hence the energy consumed by the solenoid is the area product above and below the curve. Now the area above the curve is constant since the total voltage induced, E, is proportional to the total number of lines of force cut which is constant. Thus the work done by the electrical energy supplied depends only on the area under the curve, and hence the longer time the solenoid acts the more work it can do. The condition for maximum work may be represented by Fig. 2, where the current rises to nearly its final value before the plunger starts, which then moves in such a manner as to keep the current constant until the end of the motion.

This diagram will serve to derive an expression for the maximum work. The electrical energy consumed is

$$W=\int e\,i\,d\,t=i_0\int e\,d\,t$$

but

$$\int e\,d\,t=E=\text{constant.}$$

Hence

$$W=i_0\,E=i_0\,n\,\phi\,10^{-8}=i_0^2\,L$$

but the magnetic energy stored at the completion of the motion is

$$W_1=\frac{i_0^2\,L}{2}$$

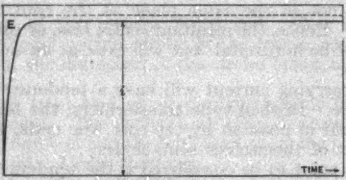


FIG. 2

Therefore the maximum mechanical work is

$$W_2=W-W_1=\frac{i_0^2\,L}{2}$$

which is one half of the electrical energy consumed; or the maximum efficiency of a solenoid is 50 per cent.

—— **Harper:** With particular reference to that portion of Dr. Steinmetz' paper which has to do with stresses in transformers, it will, perhaps, be interesting to present certain tests, the results of which are very gratifying indeed, and to discuss some of the peculiar conditions that are likely to exist in practice

The expression $F=\dfrac{810\,e_0\,i_0}{f\,l}$ g-cm., or $\dfrac{0.706\,e_0 i_0}{f\,l}$ in. lbs. formula (**54**) is readily verified by simple tests, performed with two similar coils, one being horizontally suspended directly over the other.

Two series of such tests were compiled some two years ago with arc light reactance coils, at Lynn and are shown here, tabulated. One set of tests shows an error of approximately 7½ per cent, while the other gives an error of approximately 6½ per cent.

It is seen that in both cases the calculated value is lower than the test value. This is probably due to the fact that the voltages have not been properly corrected for *I R* drop.

Another series of tests were performed at Pittsfield some two months ago, the error of which is approximately 2½ per cent. This value is well within the accuracy limits of the measuring apparatus.

The force thus determined, which may be called a horizontal force for convenience may, under certain conditions, be made up of components which are likely to be dangerous.

If, for instance, in that portion of the coils of shell type transformers which project beyond the core, the primaries are not directly opposite the secondaries, but have the effect of being staggered as shown, a couple exists, which tends to warp the coil. The centre line of magnetic gravity of the primaries is not in the same plane as the centre line of the secondaries. Hence, the resultant centre line, or direction of the force will not be horizontal, but will exist at an angle as shown in the figure.

Any coil carrying current will have a tendency to assume a circular shape. In shell type transformers, the legs of the coil are firmly held in position by the core, the ends, however, will tend to form of themselves semi-circles.

One other point to be considered is the tendency of a coil to form of itself a cable.

It should be remembered that the intensity of leakage flux is not uniform throughout the width of the coil, but is greater at the centre of the coil (if the coil be imbedded in iron). If then, a short circuit exist, the coil will have a tendency to buckle, and should it not be sufficiently strong to overcome this tendency, and its equilibrium be disturbed, the forces of conductor upon conductor (the value of which may be determined from formula (57) of Dr. Steinmetz' paper) will not lie in the same plane, and hence are liable to break the insulation tapings, and pile up on each other at the point of most intense density.

F. C. Green: A few instances of the effects of electromagnetic forces that have been observed in the practice of using transformers, will be given.

Seven or eight years ago some transformers returned from a large power plant, were observed to have the ends of the outside coils flared, as shown in Fig. 1. This was among the first instances to be brought to the attention of the designing engineers. To prevent the distortion of the coils at the ends, supporting strips were arranged as shown in Fig. 1. After the adoption of this construction no more trouble was experienced with the flaring of the ends of the coils, but as the power installations became larger and larger, it was found that under short circuit conditions, the coils were entirely collapsed and twisted. The tendency seemed to be to make cable of the vertical portions of the coil. Mr. Harper pointed out that the portions of the coil outside of the iron tend to take a circular form under short circuit. No effect of this kind has been noticed except at the corners of the coil. Here a number of instances of almost perfect circles of the copper conductor have been observed, the diameters of the circles being, however, from 1 in. to 2 in.

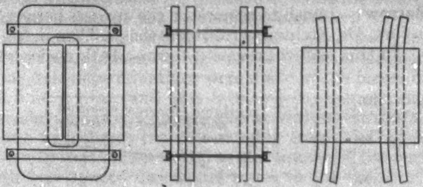


Fig. 1

Nothing has been said about electromagnetic forces in core type transformers. The dotted lines (Fig. 2) show the position of the low tension coil and the solid lines show the position of the high tension coil. Under short circuit, according to the mathematics that have been developed, the force in this case is exerted horizontally, and there is little tendency to produce motion upward or downward. If we assume that the center of the primary coincides with the center of the secondary, then there can be no motion in the vertical direction, but it is found that considerable damage is done occasionally from the forcing of either the primary or secondary coil up into the iron. In most instances, the secondary is forced up. A better idea of the magnitude of electromagnetic forces is obtained in the destruction of core type transformers than in the destruction of the shell type, for the simple reason that while the core type coils are supposed to have their centers coincide approximately, they never do exactly, and so the force to produce vertical motion is exerted at such an angle as to make this force only a very small per-

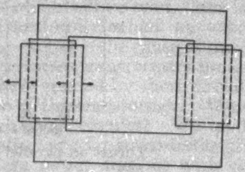
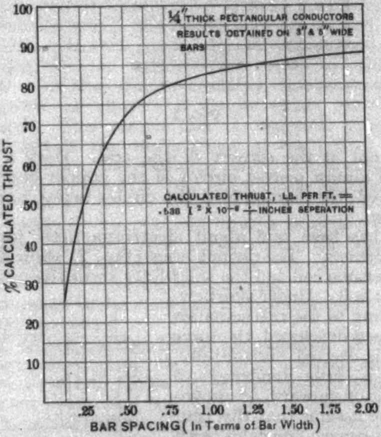


Fig. 2

Fig. 3

centage of the total force exerted between the primary and secondary. If the centers of the primary and secondary were exactly coincident the entire force would be exerted in a horizontal direction, and there would be no tendency for either coil to move vertically; but it seems that for mechanical reasons the secondary usually extends a little higher than the primary, resulting in the relation of forces indicated in Fig. 3. Of course whether the primary or secondary is forced up depends upon which one has its center line above the center line of the other.

C. J. Barrow: I wish to remark on the stresses between parallel conductors, Dr. Steinmetz considers the problem in his general solution. In this particular case it seems a little easier and more direct to consider the stresses from the veiwpoint of the thrust on a current in a magnetic field. If we assume circular conductors and a field concentric about their centers, we can readily express the field at any point and calculate the thrust on a current in this field. The thrust on unit current (10 amperes) in a field of one line per sq. cm. is one dyne per cm. length of current acting normal to field and current. Working on this basis and converting to lbs., feet and amperes we get a formulae which exactly corresponds with that developed by Dr. Steinmetz based on the reactance of the conductors—lbs. per ft. $= 0.538\, I^2 \times 10.^{-6}$ divided by the separation of conductors centers in inches.



Thrust on parallel conductors carrying current

In the case of bus bars of rectangular section the forces are not the same as for cylindrical conductors. The field is no longer concentric about central element, but elliptical with long axis of section as major axis of ellipse and the current acted on cannot now be approximately considered as concentrated at the center of conductor. Both considerations operate to reduce the forces exerted particularly between bars on short centers; the first by reducing the average field active, and the second by necessitating consideration of the thrust on a band of current the various elements of which are not all impelled in the same direction. In order to get a line of the corrections necessary on account of these considerations as well as to bolster up our faith in calculations of the forces present in high power bases under short circuit conditions, test determinations were made of the forces obtaining between 3 in. x ¼ in., and also 5 in. x ¼ in. bars arranged with faces parallel on various centers and at various currents. These tests made with direct currents ranging from 1000 to 8000 amperes, showed that forces varied as the square of the current and that with bars spaced on centers equal to the width of the bar about 80 per cent of the calculated forces obtained. At greater spacing larger values and at shorter spacings smaller values were found. Plotting results as per cent of calculated forces against spacing in terms of the width of bar used, the curves for 3 in. and 5 in. bars were found to coincide closely and it is felt that the curves obtained apply approximately to any width of bar. The results were obtained on bars ¼ in. thick. As bar thickness increases, cylindrical conductors are approached so with thicker bars somewhat higher results are to be expected.

Henry Pikler: In the present paper, also in some of the papers read yesterday, and in papers which will be read, there is much more said about forces in transformers than we were accustomed to hear about in the past. What is the cause of this? Nothing else but that perhaps recently more transformers broke down, due to forces which arose in them created by short circuit which occurred on the secondary side of the transformer. Why do transformers go to pieces by such short circuits? We used to have transformers of small and also very large capacities in the past; we used to have very large power stations with so called unlimited power; why is it that at present transformers are more likely to be ruined by short circuits than in the past? The answer, to my mind, is this: The art of making insulating materials has advanced rather rapidly and the properties of insulating materials were greatly improved, the mechanical construction of the transformer, however, has not kept pace with it, particularly the mechanical construction of the windings and their supports. From the very extended discussion already heard, on this subject, it seems to me that we have all received the impression that the windings of a transformer, particularly of the type of transformers which were shown here, are very weak mechanically, and that their supports are also very weak. When the insulating materials are improved, the high and low tension windings are brought closer together, consequently, the reactance of the transformer is diminished, and the forces arising on short circuits will be greatly increased. Hence, the weakness of the mechanical construction will be more apparent. Although it is very important to have a sufficiently high reactance in the transformer windings, this idea is not new —several years ago the results of investigations were published on this subject in the *Elektrotechnische Zeitschrift.** This idea was also embodied in transformers of large size with unlimited power behind, with successful results. The main trouble, as I see it, lies in the mechanical construction: The entire mechanical construction of the large shell type transformers, coils of which were exhibited here to-day, is such that it does not admit the proper supporting of the windings and does not permit of a solid interlocking between these windings, and the windings and core.

As to the calculation of these forces as given by Dr. Steinmetz, the derivation of the formulas is elegant, and the results are simple. The question is, however, whether they apply to actual conditions. I do not think they do. Those gentlemen who stated that they made actual tests and found that the results checked up very well with the formula given, I believe did not make those tests under actual operating conditions. I wish to ask if any of these gentlemen measured the forces in a transformer on a short circuit with unlimited power behind? I hardly think they did. An agreement with the formula was found as the result of tests made under conditions as may be found in the laboratory. If you take a transformer and short circuit it on one side and then gradually apply voltage to the other end until you reach any desired current, you will find that this current, which is called the short circuit current of the transformer, is proportional to the impedance voltage of the transformer. Also the forces will be found to be in proportion with the reactance, one of the components of the transformer. But when you have a transformer on the line, and *then* suddenly apply a short circuit on the secondary side, or you short circuit first the secondary side of the transformer and then suddenly switch the transformer to the line, you will find that the short circuit current and the forces arising in the transformer will be quite different from those given in the formula. These will depend upon the magnetic conditions of the transformer at the moment of the short circuit, that is the magnetic condition of the iron core and the relative phase relations of the current in the primary and secondary winding.

The analysis of the formula alone, as obtained by Dr. Steinmetz, is not sufficient for finding a remedy that will prevent the wrecking of the transformer windings by the forces arising on short circuits. It is necessary to go back to the derivation of the formula, to the place where Dr. Steinmetz allowed the coils to move a certain distance in order to transform the potential energy into kinetic energy. Here is the salient point. The transformer must be constructed so as to preclude any such motion of the windings on short circuits.

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*Grosze Transformatoren für Electrochemische Zwecke, by Vanidzian —Jan. 24, 1909.

John J. Frank: The reason the subject of stresses in alternating current transformers is of greater importance now than formerly is because ten or twelve years ago transformers were connected to lines in which the power back of them was relatively small. The recent combination of power plants into big systems gives practically an unlimited amount of power as far as small transformers are concerned. Small transformers which heretofore might have been rather weak in mechanical construction, but did stand up under short circuit conditions, are now not capable of doing it.

I do not believe that under actual operating conditions a break-down usually occurs the first time the strain is applied. A certain milling occurs in the core type as in the shell type, and it is only after repeated short circuits that the transformer fails and we get the twisting of the coils of the shell type transformer and the displacement of the coils of the core type transformer

Charles F. Scott: As remarked by the last speaker, the trouble is often not with the transformer, but with the power plant. In one case some large transformers were installed in a station of some 12,000 kw. and behaved beautifully for a number of years. They then began to break down, due to the fact that more generators had been added, and the short circuit currents were much larger. Although formulæ and diagrams are interesting, they do not give any adequate idea of what these forces are, compared with what one gains from an inspection of transformer coils which have been badly distorted. Coils of copper of large section bent around at sharp angles, and twisted up in great contortions, give an idea of a force away beyond our ordinary conceptions of the force of the magnetic field. I remember one case which I think is different from those mentioned, in which one part of a coil was peculiarly distorted. The coil was wound as a single layer of square wires about as large as one's finger—a part of the wires of the layer had been twisted and bent around in a most remarkable way, as part of the coil had slipped over on the other part. By a careful analysis of the position of the wires I found that a part of the primary coil had short circuited, and acted as a secondary in relation to the rest of the primary, setting up terrific forces within the coil itself, part acting as primary and part as secondary.

H. C. Cox: For the past eighteen months it has been the practice of the transformer testing department with which I am connected to subject all core type transformers of over 50 kw. capacity to a short-circuit test of five times rated current, applied suddenly on lowest tap connection through the make and break of an oil switch. During this period but one case (easily remedied by tightening coil supports) of coil displacement has been found.

Since the convention a 55 kw. transformer was subjected, out of oil, to twenty-seven times rated current without injury. Aside from heating and excessive vibration of core laminations no effect of the strain was apparent.

V. Karapetoff: Dr. Steinmetz's paper contains no literature references, nor does he give credit to previous investigators of the subject. Therefore, the following references may be of interest. His formula (**16**) has been known for at least twenty years; it can be found in the 1890 edition of Vaschy's " Traité d' Electricité et de Magnetisme ", Vol. II, p. 35. For the principle upon which it is based see Maxwell's " Electricity and Magnetism ", Vol. II, Art. 580.

The general theory and design of tractive electromagnets from the point of view of energy was given by Fritz Emde in his series of articles " Zur Berechnung der Elektromagnete " in *Elektrotechnik und Maschinenbau*, 1906, p. 945; also in the *Elektrotechnische Zeitschrift*, 1908, p. 817. He gives a proof of Kelvin's law that, when the currents in an electromagnetic system remain constant during a deformation of the system, the energy supplied by the sources of e.m.f. is divided equally, one half being converted into mechanical work, the other half increasing the stored magnetic energy of the system. From this law Steinmetz's equation (**16**) follows directly, because $\frac{1}{2} i_0^2 \, d L$ represents the increase in stored magnetic energy, and $F g \, d l$ is the mechanical work. Fritz Emde also proves that, when the flux does not change during the motion, the source of energy supplies only the $i^2 r$ loss. This theorem leads directly to equation (**33**) in Steinmetz's paper.

Emde's investigations have been lately taken up by Mr. E. Jasse (*Elektrotechnik und Maschinenbau*, 1910, p. 833) who has considerably simplified Emde's theory and applied the results to the calculation of performance of a number of commercial forms of electromagnets. Designers of electromagnets will find Jasse's articles very helpful in their work.

Mr. C. R. Underhill deserves considerable credit for a large number of tests on electromagnets. The results were published at different times in the *Electrical World*, and have been lately reprinted in his book entitled " Solenoids, Electromagnets, and Electromagnetic Windings ". Professor Silvanus P. Thompson's pioneer work on electromagnets is well known. I wish only to mention his paper on the subject before the St. Louis International Electrical Congress in 1904; the paper will be found in Vol. I of the TRANSACTIONS of the congress.

The relation which connects the mechanical force between the windings of a transformer and its magnetic leakage is treated in Alex. Russell's " Alternating Currents ", Vol. II, p. 234, in application to the theory of the constant-current floating-coil transformer. Russell's treatment is more correct than Dr.

Steinmetz's because the former considers an infinitesimal displacement of the coils, while Dr. Steinmetz bases his deduction upon a finite displacement until the two coils coincide.

Formula (**56**) for the repulsion between two conductors is as old as Monsieur André Marie Ampère (1775-1836), and in fact was first given by him. It can be derived in the C.G.S. system as follows: The flux density at a distance x from a straight infinite conductor carrying a current i is $B = 2\,i/x$ (law of Biot and Savart). According to Laplace's law the mechanical force is $F = B\,i\,l$, where l is the length of the second conductor. Hence, $F = 2\,l\,i^2/x$. It is hardly logical to derive this simple result from the variation of self-induction of the loop, because the expression for the inductance itself is originally derived from the law of Biot and Savart. The proof given in Steinmetz's paper will be found in Russell's "Alternating Currents", Vol. I, p. 63.

The preceding references are made not to detract from Dr. Steinmetz's work, but to place the proper credit where it belongs, and to enable those particularly interested in the subject to become oriented in the available literature. In this connection, I wish to make a general plea that papers presented before the Institute be provided with ample literature references, especially giving credit to foreign authors and to papers in foreign publications. The Board of Directors has lately made a highly commendable step in the direction of international courtesy and coöperation, by requiring the numerical values in the Institute papers to be given in the metric system. Requiring proper credit for priority in research and investigations would be in line with this amicable policy, and would greatly enhance the standing of our TRANSACTIONS abroad.

Considerable advantages would accrue to ourselves if the Institute papers were always provided with the most important literature references, namely

1. Repetition would be avoided, papers would be shorter, and the TRANSACTIONS less bulky.

2. Interest would be stimulated to reading or at least referring to many excellent standard works, at present hardly known at all among our engineers.

3. Study of a particular topic would be facilitated beyond the limits of a particular paper.

4. Each paper would be more liable to represent a truly new contribution to the subject, a contribution standing in a definitely stated relation to what is already known, instead of resembling sometimes a chapter from a text-book.

5. The spirit of coöperation would be more emphasized in which many investigators contribute their share to a complete solution of an engineering problem, instead of each working without due regard to the labors of others, duplicating their work, and thus making it extremely difficult for one to become oriented in the present status of knowledge in a particular topic.

K. Faye-Hansen: When dealing particularly with the short circuit stresses in alternating current transformers, Dr. Steinmetz has (without specially mentioning it) assumed that at constant current the force exerted by the magnetic leakage flux is the same for the whole distance of movement l until the magnetic centres of the coils coincide. This is however not correct as when the movement has gone so far that the current carrying parts of the two coils touch each other, the magnetic force against any further movement will be decreased. The short circuit stresses figured by Dr. Steinmetz are therefore too low (neglecting the error in decimals). I think that the subject can be handled equally correctly and simply by directly figuring the forces on the current carrying wires due to the magnetic field in the transformer under short circuit conditions. We find that the maximum force is equal to:

$$F=\frac{B}{2}\, n\, i_0\, \sqrt{2}\, d\, \frac{10^{-1}}{981} \text{ grammes} \tag{1}$$

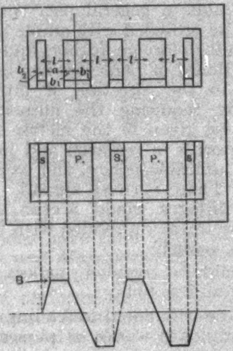


FIG. 1

Where B is the maximum induction in lines per sq. in. between the primary and secondary coils, and $\frac{B}{2}$ is the average of the (max.) induction through the coil: n the number of primary turns; i_0 the effective primary short circuit current in amperes and d the mean length of the turns in cm.

Assuming the form of field as shown in Fig. 1, the volts induced in the primary coils

$$e_0=4.44\, B\left(a+\frac{b_1+b_2}{3}\right) d\, f\, n\, 10^{-8} \tag{2}$$

The value for $B \times d \times n$ obtained by this is substituted in formula (**1**) gives:

$$F = \frac{i_0 e_0 \sqrt{2} \times 10^8 \times 10^{-1}}{981 \times 2 \times 4.44 \left(a + \frac{b_1 + b_2}{3}\right) f} \quad \frac{i_0 e_0 1620}{f\left(a + \frac{b_1 + b_2}{3}\right)} \text{ grammes} \qquad (\mathbf{3})$$

While if the same dimensions and notations are brought into Dr. Steinmetz's formula No. 54 the result is

$$F = \frac{i_0 e_0 1620}{f\left(a + \frac{b_1 + b_2}{2}\right)} \text{ grammes (the maximum force).}$$

It will thus be seen that the forces figured by Dr. Steinmetz may be as low as two-thirds of those figured under the assumption of the field form given above.

For the actual transformers the difference between the two methods of calculating will however be less than indicated above and usually in the neighborhood of 15 per cent to 25 per cent depending on the ratio between a and $(b_1 + b_2)$, *i.e.*, on the voltage, size and design of the transformer.

There is one more point to be remembered—the forces figured above are those which occur when the short circuit current of the transformers has reached its final value. The influence of current rushes however has been neglected. For the first cycles (according to the point of the voltage wave at which the short circuit is switched on)the current may be up to twice its final value and the forces equal to 4 times the value given in the formula.

The method given above for figuring the short circuit stresses in transformers has a further advantage over that given by Dr. Steinmetz—that an estimate of the forces due to the leakage lines bending over the coils can be made using formula (**1**) if only the lines of force are drawn in (as they would be expected to be) according to the relative size and position of the coils, and similarly an idea can be formed regarding which parts of the coils have to withstand the largest forces.

Dr. Steinmetz' conclusion that the short circuit stresses are inversely proportional to the leakage reactance of the transformer is on the face of it correct, but as the distance between the coils and thickness of them play an important part (as shown in the formula) regarding the forces and also influence the leakage reactance, it will be found that the forces really alter considerably more than in inverse proportion to the leakage reactance at given output, frequency, etc.

J. Murray Weed: For the mechanical forces in a transformer due to the magnetic leakage field, I have obtained results from the fundamental expression

$$S = \frac{B^2}{8\pi} \qquad (\mathbf{1})$$

which are identical with those which Dr. Steinmetz has derived. This expression gives, in dynes per sq. cm., both the stress of tension in a direction parallel to the field, and that of compression at right angles to the field. It is the stress at right angles to the leakage field which constitutes the pressure between primary and secondary windings in the transformer, and the approximate value of B which produces this stress may be calculated by the formula

$$B = \frac{\sqrt{2}\, 4\, \pi\, n\, I}{10\, l\, G} \qquad (2)$$

where n is the number of turns in the transformer, I is the effective current, l is the length of the leakage path in centimetres and G is the number of groups of coils. A group of coils here signifies a portion of both primary and secondary windings, with equivalent numbers of turns, adjacent to each other at one surface only. The groups are assumed all equal, so that $n\, I/G$ is the number of primary or secondary amperes turns per group. Substituting the value of B, we have

$$S = \frac{4\, \pi\, n^2\, I^2}{100\, l^2\, G^2} \qquad (3)$$

The area of the surface in which this stress is found is

$$A = (M\, L\, T)\, l \qquad (4)$$

where $(M\, L\, T)$ is the mean length of turns. We have therefore, for the maximum force between adjacent primary and secondary coils

$$F_{max} = S\, A \qquad (5)$$

$$= \frac{4\, \pi\, n^2\, I^2\, (M\, L\, T)}{100\, l\, G^2} \text{ dynes} \qquad (6)$$

$$= 2.82\; 10^{-7}\, \frac{n^2\, I^2\, (M\, L\, T)}{l\, G^2} \text{ lbs.} \qquad (7)$$

These equations give the force for any transformer having n turns, arranged in G equal groups, with a mean length of turn $(M\, L\, T)$ and a length of leakage path l, and with the current I flowing. The force increases with the square of the current, and will have its maximum value when the transformer is short circuited. If the primary terminal voltage is maintained, this current is limited only by the impedance of the transformer, and if the reactance element of the impedance predominates, as it must do in order to give at the same time good efficiency and a proper limitation of the mechanical forces which we are considering, no important error will be introduced by substituting the reactance for the impedance. This reactance may be expressed in terms of the design characteristics of the transformer by means of a formula which, with various empirical modifications, is familiar to designers. Thus,

$$X = \frac{20\,f\,n^2\,A'}{10^8\,l\,G^2} \tag{8}$$

The short circuit current is, therefore

$$I_{(sc)} = \frac{E}{X} = \frac{10^8\,l\,G^2\,E}{20\,f\,n^2\,A'} \tag{9}$$

where A' is the effective combined area of the leakage paths in square inches and l is their length, in inches. If we express A' in terms of its two dimensions, this equation becomes

$$I_{(sc)} = \frac{10^8\,l\,G^2\,E}{20\,f\,n^2\,(M\,L\,T)\,w} \tag{10}$$

where w is the effective combined width of the leakage paths. It should be noted in equation (**7**) that, since we have one length on the numerator, $(M\,L\,T)$, and one in the denominator, l, these lengths may be expressed in inches instead of centimetres without affecting the result.

If we substitute the value of I from equation (**10**) for one of the factors in equation (**7**) we have

$$F_{max} = 1.41\,\frac{I_{(sc)}\,E}{f\,w} \tag{11}$$

In Dr. Steinmetz' equation (**54**), if we express F in pounds and l in inches, and divide by G to obtain the force acting on a single group, and then multiply by 2 to obtain the maximum force, we have

$$F_{max} = 1.41\,\frac{I_{(sc)}\,E}{f\,G\,d} \tag{12}$$

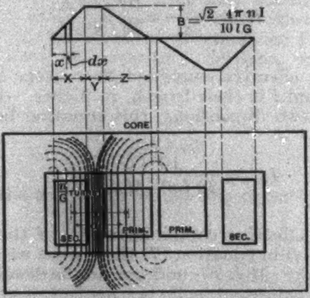
(If Dr. Steinmetz will pardon me for using the letter 'd' in the place of his 'l', I prefer to do this, because of the conventional use of 'l' for the length of the magnetic leakage path.)

If we write

$$w = G\,d \tag{13}$$

and this I think Dr. Steinmetz will grant me, equations (**11**) and (**12**) are the same. This says nothing however, for the accuracy of the assumptions made regarding the effective dimensions of the magnetic leakage field, since any errors in these assumptions eliminate themselves in the calculations. That it is impossible to assign specific dimensions to the leakage field, is illustrated by the easily recognized fact that the length of the leakage path is considerably greater for those portions of the windings which extend beyond the core in the shell type transformer than it is for those portions within the core.

The fact just stated results in a much reduced value of B for that portion of the windings which extend beyond the core, and consequently in a very much reduced stress. In other words, those portions of the windings which extend beyond the core are not subjected to nearly such great stresses as those portions within the core.



SECTION THROUGH ONE HALF OF SHELL TYPE TRANSFORMER WINDING IN TWO GROUPS

If, now, we return to equation (**7**), and substitute from equation (**10**) for both the factors I, we have

$$F_{max} = 7.05\ 10^6\ \frac{l\, G^2\, E^2}{f^2\, n^2\, w^2\, (M\, L\, T)}\ \text{lbs.} \tag{14}$$

Equation (**14**) will be more useful to the designer than equation (**12**), since it shows the effects of changes in the design characteristics, including the number of primary turns, (if E is the primary voltage), the number of groups into which the windings are separated and the various dimensions.

Dr. Steinmetz' method of developing his equation (**54**) seems to involve the conception of a uniform force acting throughout the hypothetical motion of the coils. As a matter of fact, this force would be uniform, and maximum, from the time when motion begins until the adjacent boundaries come together, but would suffer a rapid reduction thereafter, until the centers of the coils coincide, when no force would exist. In order to obtain by equation (**54**) the value of the force active before motion begins (the actual force existing in the transformer), it is necessary to use a value for the length d (Dr. Steinmetz' "l"), which is less than the total distance between coil centers, and such that its product with the initial force will equal the summation of all the products of differential distances and their corresponding forces. This value of d may be determined from the derivation of the reactance formula.

If we multiply equation (**8**) through by I, and express A' in terms of its dimensions, we have

$$\text{React. } E = \frac{20 f n^2 I (M L T) (\overline{G d})}{10^8 l g G^2} \qquad (\mathbf{15})$$

This equation is derived as follows. Starting from the left hand end of the core window as illustrated in the figure, and passing through the windings toward the right, the density of the magnetic leakage flux may be plotted as illustrated by the curve at the top of the figure, if we assume a uniform distribution of ampere turns throughout the space occupied by the windings. Assuming that the return paths of the various portions of the leakage field are as represented in the figure, that portion of the flux which exists within the first group of the secondary windings cuts out and in from the left hand side. If B is the maximum flux density between the primary and secondary coils, the density of the elementary portion of flux, within the secondary group, of dimensions $(M L T)\, d x$, is $\frac{B}{X} x$.

And if $\frac{n}{G}$ is the number of turns in the group, the number of turns cut by this elementary portion of flux is $\frac{n}{G X} x$. Adding all the elementary products of flux by turns for that portion of the flux within the secondary winding, we have

$$\int_0^X \frac{B n}{G X^2} (M L T)\, x^2\, d x = \frac{B n}{G} (M L T) \frac{X}{3} \qquad (\mathbf{16})$$

Integrating in a similar manner for that portion of the flux within the primary group, and expressing the result in equivalent secondary turns, we have

$$\frac{B\,n}{G}\,(M\,L\,T)\,\frac{Z}{3} \tag{17}$$

For that portion of flux which exists between the primary and secondary coils, the product of flux by turns is

$$\frac{B\,n}{G}\,(M\,L\,T)\,Y \tag{18}$$

the result being expressed in equivalent secondary turns for that portion of the flux which cuts through primary turns. Adding all these results, we have, for the entire group of primary and secondary coils

$$\frac{B\,n}{G}\,(M\,L\,T)\,d \tag{19}$$

where

$$d = \tfrac{1}{3}\,X + Y + \tfrac{1}{3}\,Z \tag{20}$$

The summation of flux turn linkages for the entire transformer is, therefore

$$\frac{B\,n}{G}\,(M\,L\,T)\,G\,d \tag{21}$$

Substituting this value in the fundamental voltage equation

$$E = \frac{\sqrt{2}\,\pi\,f\,N\,\phi}{10^8} \tag{22}$$

we have

$$\text{React. } E = \frac{\sqrt{2}\,\pi\,f\,n\,B\,(M\,L\,T)\,G\,d}{10^8\,G} \tag{23}$$

Substituting again for the value of B from equation (**2**), and expressing dimensions in inches, we obtain equation (15).

The development of formulæ similar to (**15**) have appeared in various text books, and it has been given here only for the purpose of finding the length of *d*, (Dr. Steinmetz' *l*), which he has called the distance between the magnetic centers, but which I would call the effective width of the magnetic leakage path for one group of coils. This has been found to be the distance between primary and secondary plus $\frac{1}{3}$ of the distance through primary, plus $\frac{1}{3}$ of the distance through secondary, which is less than the distance from coil center to coil center by $\frac{1}{6}$ of the distance through primary plus $\frac{1}{6}$ of the distance through secondary.

I should like to add, with reference to the formula for reactance, that various empirical modifications are in use, based upon different assumptions as to the dimensions of the leakage path. Also that the linkage of the secondary by leakage flux, as assumed by the return paths shown in the figure, has been questioned. I agree with those who criticize this assumption to the extent that for every linkage of leakage flux with the secondary there must be an equivalent linkage of the main flux in the opposite direction, and wherever these fluxes would occupy the same path, the evident result is the elimination of the secondary linkage. This condition does not exist throughout, however. Thus, for that portion of the winding of a shell type transformer which is outside of the core only the leakage flux exists, the main flux being confined practically to the core. It is a fact, however, that the reactance of the transformer, obtained from the integration of flux turn linkages, will be the same for the given distribution of leakage flux, whether the return paths are as shown in the figure, or all to the right, enclosing the primary.

H. B. Dwight (by letter): The following method of using a well-known equation to obtain some of the formulæ in Dr. Steinmetz' paper, may be interesting as an alternative proof.

The fundamental equation referred to is

$$F = \frac{H\,i}{10} \text{ dynes per cm. of conductor}$$

where H is the average magnetic field in which the conductor lies. This is proved by equating the mechanical work, $F\,d\,l$, to the electrical work, $\frac{i}{10} H\,d\,l$, when the conductor is moved a distance $d\,l$.

1. *Repulsion of Two Parallel Conductors.* The field around a long conductor is found by integrating the effect of the current on a unit pole at distance l from the wire, and is

$$H = \frac{2\,i}{10\,l}$$

The other wire lies in this average field, and the force per cm. on it is

$$F=\frac{H\,i}{10}=\frac{i^2}{50\,l}\text{ dynes}$$

$$=\frac{20.4\,i^2\,10^{-6}}{l}\text{ grams.}$$

2. *Short Circuit Stresses in a Shell Type Transformer.* During short circuit, the section of the path for the leakage flux is $m\,l$.
Where m = mean turn

$$l=a+\frac{b}{3}+\frac{c}{3}$$

a = distance between high and low tension coils.
b and c = widths of high and low tension half coils.

The density of the leakage lines is more accurately given by this value of l than by the distance between centers of half coils, which is $a+\frac{b}{2}+\frac{c}{2}$. The effective density of the leakage lines is

$$H=\frac{\phi}{l\,m}=\frac{e\,10^8}{2\,\pi\,T\,f\,l\,m}$$

where T = number of turns.

As the secondary part of a high-low group has a field H on one side, and zero field on the other, the mechanical force is that due to the average field $\frac{H}{2}$, and is

$$F=\frac{H}{2}\;\frac{i_0}{10}\;\frac{T\,m}{g\,K}\text{ grams}$$

where K = number of high-low groups
Therefor

$$F=\frac{e\,i_0\,10^7}{4\,\pi\,f\,g\,l\,K}\text{ grams}$$

which is the same result as in the paper.

From this

$$F = \frac{810\, e\, i_0}{f\, l\, K} \text{ grams}$$

which gives approximately 28 long tons for the example considered.

A. C. Zelewsky (by letter): I have read with great care the very interesting and important paper on "Mechanical Forces in Magnetic Fields" and would like to make a few remarks.

Within the last few years I have made, upon the suggestion of Mr. O. T. Bláthy, a considerable series of researches on the forces which act on the coils and conductors of machines during short circuit.

The general expression (**65**) of Dr. Steinmetz' paper for the mechanical work—or the mean force—and the derived formula (**66**) for absence of saturation, also do not seem to be expressed in the simple forms which they permit and which is a chief advantage of the other results of the paper.

By dealing first with the general system and considering the electromagnet, the transformer, and the parallel conductors only as special cases, a great deal of work may be saved. The mean force—or the mechanical work—are seldom of great interest, because generally the force for a special position or the maximum value of the force have to be determined.

Considering a differential motion of the system, the mechanical work done is

$$F\, d\, l \text{ ergs}; \tag{1}$$

the increase of stored energy is

$$\frac{d}{d\,l}\left\{\int_0^i i' \frac{\delta \varphi'}{\delta i'}\, d\, i'\right\} d\, l \text{ ergs}; \tag{2}$$

and the electric energy absorbed by the induced electromotive force is

$$-i\, \frac{d\,\varphi}{d\,l}\, d\, l \text{ ergs}; \tag{3}$$

where F is the force exerted, l is the distance in the direction of motion, i and φ are the current and flux (or flux-turns) respectively during the motion, and i' and φ' are general values of current and flux (or flux-turns) respectively as they would increase together from zero to the limits i and φ—all quantities being expressed in c.g.s. units. Applying the law of conservation of energy,

$$F = i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}\left\{\int_0^i i'\,\frac{\delta\,\varphi'}{\delta\,i'}\,d\,i'\right\} \text{ dynes,} \qquad \textbf{(4)}$$

which is equivalent to (**63**) of the paper.*

Another form of this equation can be derived by partial integration:

$$F = i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}\left|i'\,\varphi'\right|_0^i + \frac{d}{d\,l}\left\{\int_0^i \varphi' d\,i'\right\},$$

$$= i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}(i\,\varphi) + \frac{d}{d\,l}\left\{\int_0^i \varphi'\,d\,i'\right\},$$

$$= -\,\varphi\,\frac{d\,i}{d\,l} + \frac{d}{d\,l}\left\{\int_0^i \varphi' d\,i'\right\} \text{ dynes.} \qquad \textbf{(5)}$$

Both equations for *F* are quite general, as nothing has been said about saturation and both *i* and φ are supposed to change during motion. In practical units they are

$$F = 0.102\left[i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}\left\{\int_0^i i'\,\frac{\delta\,\varphi'}{\delta\,i'}\,d\,i'\right\}\right]10^{-6}\text{ kg.;} \qquad \textbf{(6)}$$

and

$$F = 0.102\left[-\,\varphi\,\frac{d\,i}{d\,l} + \frac{d}{d\,l}\left\{\int_0^i \varphi'\,d\,i'\right\}\right]\cdot 10^{-6}\text{ kg;} \qquad \textbf{(7)}$$

in which *i* is now expressed in amperes.

Considering an alternating-current system, the fluxes φ and φ' induce respectively the electromotive forces

$$e' = 2\,\pi\,f\,\varphi'\,10^{-8} \text{ volts,} \qquad \textbf{(8)}$$

and

$$e = 2\,\pi\,f\,\varphi\;10^{-8} \text{ volts.} \qquad \textbf{(9)}$$

***Integrating,** $W = \int_0^l F\,d\,l = \overline{F}\,l = \int_0^l i\,\frac{d\,\alpha}{d\,l}\,d\,l - \left|\int_0^i i'\,\frac{\partial\,\phi}{\partial\,i'}\,di'\right|_0^l$ **ergs, which is of exactly the same form as (63) except for differences of notation. [Ed.**

Substituting these values of the fluxes in terms of the impressed electromotive forces, we have in practical units

$$F = \frac{0.810 \times 2}{f} \left[i \frac{d\,e}{d\,l} - \frac{d}{d\,l} \left\{ \int_0^i i' \frac{\delta\, e'}{\delta\, i'}\, d\,i' \right\} \right] \text{kg.}, \tag{10}$$

and

$$F = \frac{0.810 \times 2}{f} \left[-e \frac{d\,i}{d\,l} + \frac{d}{d\,l} \left\{ \int_0^i e'\, d\,i' \right\} \right] \text{kg.} \tag{11}$$

If saturation is absent—and in most cases it can with great approximation be supposed so—the flux is proportional to the exciting current:

$$\varphi' = L\, i'; \tag{12}$$

so that

$$\int_0^i i' \frac{\delta\, \varphi'}{\delta\, i'}\, d\,i' = \int_0^i \varphi'\, d\,i'. \tag{13}$$

Adding (**6**) and (**7**) and substituting (**13**),

$$F = 0.051 \left[i \frac{d\,\varphi}{d\,l} - \varphi \frac{d\,i}{d\,l} \right] 10^{-6} \text{ kg.} \tag{14}$$

Similarly from (**10**) and (**11**),

$$F = \frac{0.810}{f} \left[i \frac{d\,e}{d\,l} - e \frac{d\,i}{d\,l} \right] \text{kg.} \tag{15}$$

(**14**) may also be written:

$$F = 0.051 \left[2\, i \frac{d\,\varphi}{d\,l} - \frac{d}{d\,l} (\varphi\, i) \right] 10^{-6} \text{ kg.}; \tag{16}$$

or

$$F = 0.051 \left[-2\, \varphi \frac{d\,i}{d\,l} + \frac{d}{d\,l} (\varphi\, i) \right] 10^{-6} \text{ kg.} \tag{17}$$

(**15**) may also be written:

$$F=\frac{0.810}{f}\left[2\,i\,\frac{d\,e}{d\,l}-\frac{d}{d\,l}(e\,i)\right]\text{kg.}; \tag{18}$$

or

$$F=\frac{0.810}{f}\left[-2\,e\,\frac{d\,i}{d\,l}+\frac{d}{d\,l}(e\,i)\right]\text{kg.} \tag{19}$$

These equations have also other forms which may be useful in special cases. Introducing reactance,

$$x=\frac{e}{i}\text{ ohms,} \tag{20}$$

we obtain the three formulas,

$$F=\frac{0.810}{f}\,e\,i\,\frac{d}{d\,l}\left(\log_\epsilon\frac{x}{x_0}\right)\text{kg.,} \tag{21}$$

$$=\frac{0.810}{f}\,i^2\,\frac{d\,x}{d\,l}\text{kg.,} \tag{22}$$

and

$$=-\frac{0.810}{f}\,e^2\,\frac{d}{d\,l}\left(\frac{1}{x}\right)\text{kg.} \tag{23}$$

If x is constant during motion, no force is exerted

If either the current or voltage are constant,

$$F=\pm\frac{0.810}{f}\,\frac{d}{d\,l}(e\,i)\text{ kg.} \tag{24}$$

where $e\,i$ is the volt-amperes of the system. This is equivalent to equation (**54**) of the paper.

In transformers the kilovolt-amperes at short-circuit are easily determined knowing the potential difference at the terminals and the leakage. Supposing the leakage to be proportional to the distance l between magnetic centers of primary and secondary coils, then

$$\frac{d}{d\,l}(e\,i)=\frac{e\,i}{l}, \tag{25}$$

and

$$F = \frac{0.810}{f}\ \frac{e\,i}{l}\ \text{kg.} \tag{26}$$

—again the same result as in the paper.

Two parallel conductors are repelled with a force which may be determined from the above equations, considering that

$$\frac{d\,x}{d\,l} = \frac{d}{d\,l}(2\,\pi\,f\,L) = 2\,\pi\,f\ \frac{4\times10^{-9}}{l} \tag{27}$$

and substituting in (22),

$$F = 20.4\ \frac{i^2}{l}\ 10^{-9}\ \text{kg. per cm. length} \tag{28}$$

—exactly the same result as (57) of the paper.

Much simpler indeed would it be to start from the formula

$$F = i\,\mathfrak{B}\ \text{dynes per cm.,} \tag{29}$$

in which $\mathfrak{B}$ is the flux density at the axis of the conductor. Here

$$\mathfrak{B} = \frac{4\,\pi\,i}{2\,\pi\,l} = \frac{2\,i}{l}\ \text{gausses;} \tag{30}$$

so that

$$F = \frac{2\,i^2}{l}\ \text{dynes per cm.,} \tag{31}$$

or in practical units,

$$F = 20.4\ \frac{i^2}{l}\ 10^{-9}\ \text{kg. per cm} \tag{32}$$

as already given.

E. Jasse (by letter): I would like to call attention to an article covering the same subject which I published in "*Elektrotechnik und Maschinenbau*", *Zeitschrift des Elektrotechnischen Vereines in Wien, Heft* 40, 41 *u.* 42, 1910. In this article the equations 5, 6, 15*a*, 7 and 15*b* are equivalent to equations 1, 11, 16, 33 and 37 of Dr. Steinmetz's paper.

C. P. Steinmetz: Professor V. Karapetoff's historical review of the theories used in my paper is very interesting and important if complete. I never give literary references, however, for the reason which I stated in the preface of my first book:

"I have omitted altogether literary references, for the reasons that incomplete references would be worse than none, while complete references would entail the expenditure of much more time that is at my disposal, without offering sufficient compensation". (A. C. Phenomena, 1897).

As it is obvious that no paper has ever been written, which does not use the work of preceding investigators, the absence of literary references does not claim originality for every detail. When crediting priority of a conception however, the serious danger is the possibility of unfairness, by overlooking the first publication on the subject, and thereby giving credit where it does not belong. This can be guarded against, to some extent, only by such an extensive search of the literature, as is usually out of the question. Nevertheless, it is undoubtedly desirable, at least historically, to give references. This however is work, which the college professor can do very much better than the practicing engineer, as he has the time and the facilities, and I therefore express the hope, that our colleges will undertake this work of keeping the historical records of the electrical engineering science.

That the mechanical forces, with which my paper deals, are not a mere theoretical conception, but are very real, no one can gainsay who has had anything to do with transformers which have passed through a short circuit. I mean transformers of large size, built with very close regulation, from mistaken engineering notions, usually on the express requirement of customers which have forced the manufacturers against their better knowledge to design for a reactance of two per cent or even less. If such a 5,000 kw. transformer of close regulation passes through a short circuit on a system which really can maintain the voltage at the primary—a system with momentary short circuit power of millions of kilovoltamperes, as there are now quite a number in this country—the closest approach to the appearance of such a transformer is the way that I think two express trains must look after a head-on collision at high speed.

It is true that these destructive agencies have been at work more in the last years than before, but the reason is obvious—it is due to the systems on which the transformers are installed—we did not have these large power systems a few years ago, but they are increasing now more and more rapidly—which can maintain constant primary voltage with a secondary short circuit on a big transformer. In a small transformer the forces are relatively less, but they are enormous in big transformers, and what really was saving the transformer, and now still saves by far the largest majority of the transformers, is the inability of the generating system to maintain the primary voltage under secondary short circuit, and the forces go down with the square of the current, that is, with the square of the impressed voltage.

If for instance, as stated by one of the speakers, amongst many transformers tested, with five times full load current, one showed distortion—I think that is rather a condemnation of the mechanical construction—as at five times full load current the mechanical strains are only one hundredth of what they are at short circuit, with 50 times full load current, and a test with five times full load current thus is meaningless in indicating the ability of standing the short circuit stresses.

All engineering theory consists of three parts: first, to find out that a thing exists; second, to get the general theory, which is really the theory of the phenomenon as it would exist under ideal conditions, conditions which never exactly but only approximately exist in practice, for instance, parallel circular conductors carrying uniform current density, and the third part is the adoption of those general theories to the specific conditions under investigation, the calculation of the exact distance of the equivalent magnetic centers of the coils of the transformer which I referred to in the paper—the calculation of the equivalent location of conductor centers which represent the forces between parallel rectangular bus-bars—all these things are of importance in the investigation and consideration of the secondary phenomena which modify the effect of the primary or general phenomenon, which constitutes the subject matter of the paper, and I think it is very gratifying to see that the discussion has already extended to these secondary questions by giving us a very explicit study of the secondary actions which have to be considered in applying the general equation to the specific cases of rectangular conductors, of transformer coils, etc.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

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THE REGULATION OF DISTRIBUTING TRANSFORMERS

BY C. E. ALLEN

With the many improvements made in distributing transformers during the past few years, especially since the advent of the so-called silicon steels (by the use of which the iron loss of transformers has been greatly reduced), the tendency has been to lay particular stress upon the iron loss characteristics, with the result that other electrical characteristics, such as exciting current and regulation, have scarcely received the attention that their importance deserves. In reviewing the published claims made by the various manufacturers, we find that the two last named characteristics have not been improved in the same proportion as the iron loss. While the author recognizes that both a low exciting current and good regulation are of great importance, this paper will be confined to a discussion of regulation; its relation to the other characteristics of distributing transformers and its effect on the economical operation of the modern central station.

The regulation of a transformer operating on a non-inductive load is defined by the A. I. E. E. as " the ratio of the rise of secondary terminal voltage from rated non-inductive load to no-load (at constant-primary impressed terminal voltage) to the secondary terminal voltage at rated load." The value of the regulation of the average distributing transformer at present on the market varies from 1 per cent to 3½ per cent, and when operated on power factors as low as 60 per cent, the regulation in some instances is as high as 4 per cent.

The published regulation of the transformers of different manufacturers varies, not only due to the different designs, but also to the various methods used in making the calculations. It is customary to measure the resistance of the windings by the "fall of potential" method and the impedance of the windings by the short-circuit test, and to obtain the regulation from this data by substitution in some arbitrary formula.

The following are some of the more important formulas in use: The per cent regulation at 100 per cent power factor

$$= I\,R + \frac{(I\,X)^2}{200} \tag{1}$$

Neglecting the last term

$$= I\,R \tag{2}$$

At any power factor the per cent regulation

$$= I\,R \cos\phi + I\,X \sin\phi + \frac{(I\,X \cos\phi - I\,R \sin\phi)^2}{200} \tag{3}$$

Neglecting the last term

$$= I\,R \cos\phi + I\,X \sin\phi \tag{4}$$

At any power factor the per cent regulation

$$= 100\ \sqrt{1 + c^2 + d^2 + 2\,c \cos\phi + 2\,d \sin\phi} - 1 \tag{5}$$

At 100 per cent power factor the per cent regulation

$$= I\,R + \frac{(I\,X)^2 + 2\,I\,X\,m}{200} \tag{6}$$

At 100 per cent power factor the per cent regulation is calculated from the following formula, which gives the value of the no-load secondary terminal e.m.f.:

$$E = \sqrt{(100 + I\,R \cos\phi + I\,X\,W)^2 + (I\,X)^2} \tag{7}$$

At any other power factor

$$E = \sqrt{(100 + I\,R \cos\phi + I\,X\,W)^2 + (I\,X \cos\phi - I\,R\,W)^2} \tag{8}$$

The symbols used in the above formulas are,

$I R$ = Total resistance drop in the transformer expressed in per cent of rated voltage.

$I X$ = Reactive drop similarly expressed.

E = No-load secondary terminal e.m.f.

Φ = Angle of lag of secondary current behind secondary voltage.

Cos ϕ = power factor of load.

W = (wattless component of load plus the magnetizing current), expressed as a decimal fraction of full load current.

m = Per cent magnetizing current.

c = $I R \div 100$.

d = $I X \div 100$.

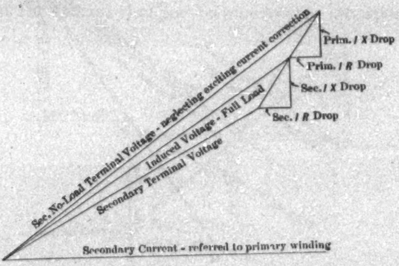
Prim. I X Drop
Prim. I R Drop
Sec. I X Drop
Sec. I R Drop
Sec. No-Load Terminal Voltage - neglecting exciting current correction
Induced Voltage - Full Load
Secondary Terminal Voltage
Secondary Current - referred to primary winding

FIG. 1

Assuming a transformer having a resistance drop equal to 1.5 per cent and a reactance drop equal to 2 per cent and a magnetizing current equal to 5 per cent, the following table gives the regulation at different power factors calculated by substitution in the above formulas:

PER CENT REGULATION

Formula	Power factor 100 per cent	Power factor 90 per cent	Power factor 80 per cent	Power factor 70 per cent	Power factor 60 per cent	Power factor 50 per cent
1 and 3	1.52	2.23	2.40	2.48	2.50	2.48
2 and 4	1.50	2.22	2.40	2.48	2.50	2.48
5	1.50	2.22	2.40	2.48	2.50	2.48
6	1.62	—	—	—	—	—
7 and 8	1.62	2.32	2.5	2.58	2.6	2.58

From the foregoing equations, it is obvious that there are few characteristics of a transformer that do not, directly or indirectly, influence the regulation. It is the belief of the author that formulas 1 to 4 give the most accurate results. The fact that a variation still exists in the methods of figuring the regulation used by the various manufacturers, indicates that the regulation has not been given the same consideration as other characteristics. Otherwise it appears that some standard method would have been adopted.

From the very definition of regulation as well as the fact that the exciting current is present in the transformer at no-load and full load, and therefore has practically the same influence at both loads, it follows that the regulation obtained by either formula (1 to 4) approximates more closely the true value. This is illustrated in Figs. 1 and 2. From Fig. 1 formulas 1 to 4 may be deduced. Fig. 2 substantiates the fact that formulas 1 and 3 are more accurate than those formulas wherein the exciting current is incorporated.

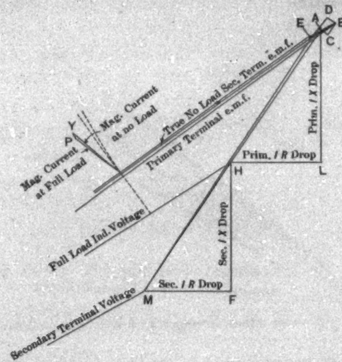
D
E
A
B
C
True No Load Sec. Term. e.m.f.
Primary Terminal e.m.f.
Prim. I X Drop
Prim. I R Drop
H
L
Y
P
Mag. Current at no Load
Mag. Current at Full Load
Full Load Ind. Voltage
Sec. I X Drop
Sec. I R Drop
M
F
Secondary Terminal Voltage

FIG. 2

From Fig. 2 it is seen that as long as the exciting current remains constant in magnitude and in phase relation to the induced e.m.f., the presence of exciting current does not affect the regulation one way or the other, but that the decrease in, and phase displacement of, the exciting current from no-load to full load has a tendency to improve the regulation.

The diminution of the exciting current is due to the fact that a large proportion of the primary impressed e.m.f. is consumed in forcing the full load current through the winding and therefore the induced e.m.f. is reduced, with resulting decrease in flux density in the iron and a corresponding decrease in exciting current. The phase displacement is due to the fact that as the exciting current is reduced in value, the iron loss component of the exciting current is reduced by a smaller percentage than the magnetizing component; this is true for values of the induction commonly used in distributing transformers. At fairly low inductions, however, the reverse of the above is true.

The vectorial change in the exciting current is shown in Fig. 2 by the line $Y P$, and the vectorial increase in the secondary induced e.m.f. is shown by $E A$.

No doubt the reason that led to incorrectly incorporating the exciting current in some of the foregoing formulas was due to its influence on the power factor in the primary windings of the transformer. A change in the power factor of the load does affect the regulation, but inasmuch as the change referred to is on the primary winding only, it does not affect the ratio of the change from no load to full load in the voltage across the terminals of the secondary winding to the full load voltage, and this agrees with the definition of regulation.

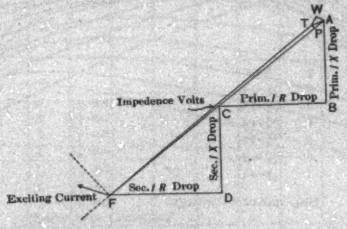

FIG. 3

The impedance is ordinarily measured by short circuiting the secondary and putting full load current into the primary of the transformer. A small component of this current must necessarily be magnetizing current so that if full load current is flowing in the primary, the secondary current is slightly less than full load. In Fig. 3 the measured impedance is equal to $F T$, the true impedance would equal $F A$. This is greater than the measured impedance by $P A$. The error introduced is, however, quite small. Furthermore, the difference between the actual voltage drop from no-load to full load, with flux and magnetizing current constant, and that calculated from the short circuit impedance, as shown in Fig. 3, is practically compensated for by the reduction of the voltage drop, due to the fact, shown in Fig. 2, that the magnetizing current is less at full load than at no-load. Therefore, the regulation resulting from formulas 1 and 3 is as correct as it is possible to obtain.

In considering the influence on regulation of the transformer characteristics, which have been claimed to be most important, it is not surprising that the regulation of modern distributing transformers is not as consistent as its importance warrants.

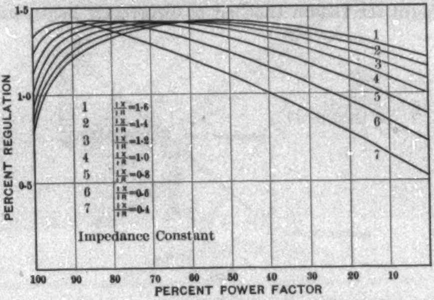

FIG. 4

This is probably due to the fact that the iron and copper losses were pre-determined and the regulation was made as low as possible consistent with these limitations. Inasmuch as the copper loss and the reactive drops are controlled directly by the pre-determined characteristics, Figs. 4 and 5 are given to show the variations in the regulation with certain given values of the $I X$ and $I R$ drop. Fig. 4 shows the variation in the regulation with the impedance constant as the power factor changes, and from this it will be seen that where circuits have a power factor greater than 70 per cent, the ratio of $\frac{I X}{I R}$ should be greater than one to obtain the best regulation for a constant impedance.

On the other hand, if the transformers are to be operated at power factors less than 70 per cent, then the ratio of $\frac{IX}{IR}$ should in general be less than one. In Fig. 5 is shown the variation in the regulation with the resistance constant and the reactance variable. From this it is seen that as far as regulation is concerned the best transformer for all power factors is one with the ratio of $\frac{IX}{IR}$ as small as possible. Fig. 6 shows that with the reactance constant and copper loss drop variable, the best transformer for all power factors, from the standpoint of regulation, is one where the ratio of $\frac{IX}{IR}$ is as great as possible. Figs. 5 and 6 are of value only in showing the variation in the regulation for certain changes in other characteristics and how regulation of a given value may be maintained by changing the construction of the windings in a transformer having the same general dimensions.

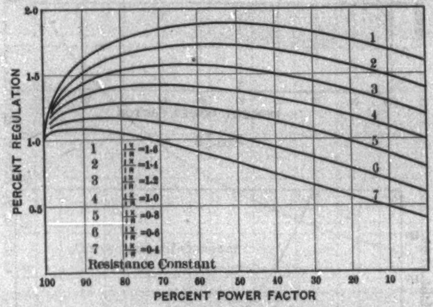

FIG. 5

It is usually impractical to obtain transformers with the best regulation unless some other characteristic is sacrificed. Therefore, each characteristic in a well balanced design should be given due consideration, and one made equally as good as another, depending upon its relative importance to the economy of operation of the average central station.

If, at the present time, the manufacturers were called upon to improve the regulation, this could be accomplished only at the sacrifice of other characteristics of the transformer, or an increase in the active material of the transformer, or by improvements in material.

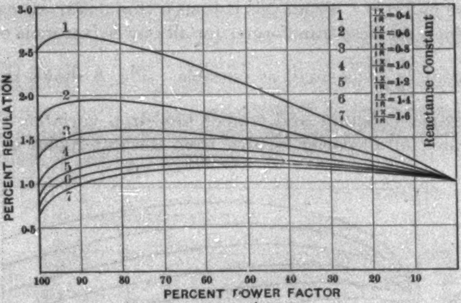

FIG. 6

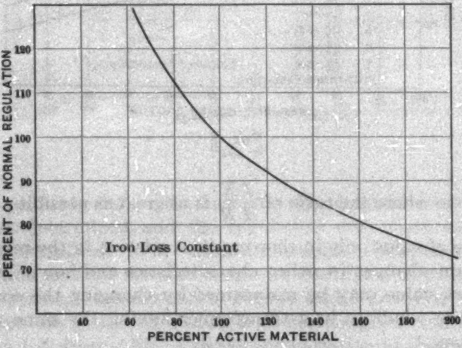

FIG. 7

In Fig. 7 it will be seen that by maintaining a constant iron loss, any reduction in the regulation would mean a considerable increase in active material necessary. It must be remembered that with the condition as shown in Fig. 7, the copper loss would also be reduced in the same ratio as the regulation. From Fig. 8 it will be seen that with the active material constant, any further reduction in the regulation must be made at the sacrifice of the iron loss, or reversing this statement, it may be said with present quality of materials that any further reduction in the iron loss would be at the sacrifice of the regulation.

Consider the relative value of the regulation as compared with other characteristics in the economical operation of a central station; taking for example one where the cost of generating is one cent per kilowatt-hour, and the energy is sold at seven cents per kilowatt-hour, this being assumed as a proportionate average of the lighting and power rates. The average full load operation per day to make the value of the regulation equal that of the iron loss would be only four hours, inasmuch as the regulation would be evaluated at six cents per kilowatt-hour. These figures are based on a power factor of 100 per cent which is, of course, higher than the average central station power factor. Considering the improvement in the lighting service obtained by the consumer when transformers of better regulation are used, it would appear that the value of the regulation is greater than that of the iron loss when the transformer is operating at full load, or its equivalent, for more than four hours per day. There are certain local conditions in every central station that tend to modify the foregoing results, such as free lamp renewals, the price of power, the cost of generating, etc.

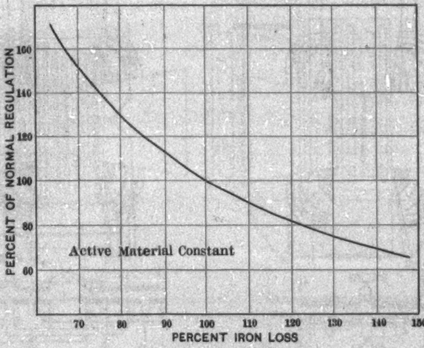

FIG. 8

While it is true that most of the central stations are adopting induction feeder regulators to compensate for the line regulation, they cannot be made to compensate for transformer regulation inasmuch as there are necessarily a number of transformers of different capacity on the same feeder which do not have the same regulation and which furthermore are not equally loaded at the same time.

To obtain a good regulation on modern transformers, when the values of other characteristics have been predetermined, resort has been made to many different methods. Fig. 9 shows the internal connections of the coils on the smaller sizes of the distributed shell type transformers, while Fig. 10 shows the interconnection of the coils on the distributing transformers of larger capacity where continuous oil ducts have been introduced to provide for the cooling. It may be noted in Fig. 10 that one of the oil ducts is placed between two sections of the high tension winding. This serves two functions, one to cool the primary, which, having a low space factor, might otherwise run excessively hot and the other to provide better regulation than would be

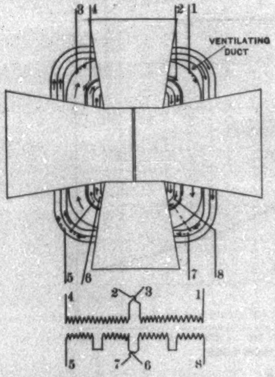

FIG. 9.—Relative arrangement of windings of small distributing transformers

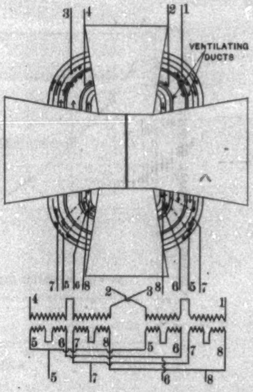

FIG. 10.—Relative arrangement of windings of large distributing transformers

obtained if the duct was placed between the low tension and high tension coils, thereby increasing the reactance. Fig. 11 shows the shell type transformer with "pan-cake" coils and it will be noted that a large number of coils are necessary in that they are interlaced, for the purpose of reducing the reactance and thereby securing a low regulation. The core type of transformer is shown in Fig. 12. It will be noted that a low regulation is obtained by long cylindrical coils without any interlacing of same.

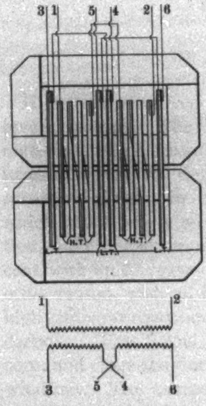

FIG. 11.—Relative arrangement of windings on shell type distributing transformer

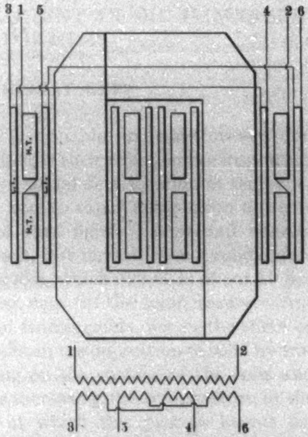

FIG. 12.—Relative arrangement of windings on core type distributing transformer

The methods of inter-connection and interlacing, as illustrated, enables as good a regulation to be obtained with the three-wire secondary operation as with the two wire service. In fact, the methods shown in these illustrations have made it possible for the manufacturers to guarantee a regulation on either side of the three wire system, when one side is loaded, and the other unloaded, to be as good as the regulation of the two wire system.

With reference again to Figs. 9 and 10, which show the latest construction of the distributed shell type transformers, it is interesting to note the method used in interlacing and connecting these windings in order to obtain the very lowest possible results for given conditions. This exemplifies the care that has been taken to obtain the very best regulation in modern transformers.

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THE TEMPERATURE GRADIENT IN OIL IMMERSED TRANSFORMERS

BY JAMES MURRAY WEED

High temperatures are objectionable in transformers for several reasons. The first of these is their effect on the insulating materials, which are subject to gradual deterioration at temperatures of about 100 deg. cent. and to rapid destruction at temperatures greatly in excess of that figure. A second reason, which is not nearly so important, but nevertheless a valid objection, is their effect upon copper loss, which increases about 10 per cent with an increase of 25 deg. cent. in the temperature. Another reason, with oil-insulated transformers, lies in the effect of high temperatures upon some oils, in the deposition of solid hydrocarbons. This forms a coating on the surface of the coils and core, and clogs the ducts, thus increasing the temperature in the windings. The temperature at which this process begins depends upon the character of the oil used. A fourth objection to high temperatures existed formerly in the aging effect of temperatures exceeding about 70 deg. cent. upon the iron used in the core, thus increasing the core loss. This objection does not exist in connection with the present improved steel, which is non-aging.

With respect to the effect of high temperature upon the insulating materials, it is the point in the windings where the temperature is maximum that is important. This temperature may be considerably higher than the average temperature, which is measured when the transformer is tested. And again, with respect to the deposition of solid hydrocarbons, this depends upon the maximum temperature to which the oil is subjected at the immediate surface of contact with the coils or core, rather than upon the temperature which is measured at the top of the oil.

A knowledge of the distribution of temperature throughout the transformer, and of the various things which affect this distribution, is important from the standpoint of those who use transformers, to enable them, for instance, to judge from the average temperature rise of the transformer windings, or better still, from the temperature of the oil at the top of the transformer, what may be the maximum temperature rise in the windings. Such a knowledge is important from the standpoint of the designer, to enable him to adopt those conditions which are most favorable to cooling, avoiding an unequal distribution of temperature, and obtaining the minimum temperature rise for a transformer of given cost and rating. Stating the case differently, it will enable him to build a transformer of a given rating, and with given temperature rise, at the minimum cost.

The general subject of temperature rise in transformers has received much attention, which may be said to fall in three classes. The first class may be termed the statistical method of investigation. By this method the temperature rise, as determined by test, is recorded without particular reference to details of design. In effect, transformers are looked upon as reservoirs of heat, all the resistance to its escape existing in two uniformly distributed layers, the one being at the surface of the transformer, and the other at the surface of the tank. From the results of the test, rules are laid down for the designer, based upon the watts per square inch at each of these surfaces. Owing, however, to variations in design which affect the temperature rise, but are not taken into account, these rules are not always safe. It thus happens that occasionally transformers are built which exceed their temperature guarantees. On the other hand, many transformers are built which operate cooler than is required, and since temperature rise is what really limits the capacity of a transformer, the actual capacity is usually more or less than that which was intended. The knowledge of temperature rise gained in this way applies reasonably well to standard types, but may be of little value for estimating the performance of a transformer which is a radical departure from standard practice, and is of no use for determining what will be the most economical design when considering new types. Nor does it at all tell us what are the maximum temperatures reached in the windings of a given transformer.

In the second class of investigation, much work has been done in testing different methods of cooling, under specific conditions, and comparing results from definite changes in these conditions. Much valuable information has been gained in this way as to the relative merits of the definite combinations of conditions tested. Such tests are made upon complete transformers, and the number of combinations of conditions tested is therefore necessarily limited to those existing in available transformers. The significance of such tests is often lost from the fact that several conditions existing in a given transformer may be different from those existing in any other transformer with which it is compared. If such a system of investigation were continued indefinitely, it is possible that ultimately the most economical design from the standpoint of cooling might be arrived at, but it would be at very great cost in "development work"—testing new ideas, making new designs, new standard lines of parts, etc., and this method also would never tell what is the maximum temperature in the windings.

A third class of investigation is that which undertakes, by a study of the laws of cooling, to formulate a correct theory applicable to the general case, which will indicate once for all that combination of conditions which is most favorable to cooling, and enable one to say with considerable accuracy not only what will be the average temperature rise in any given case, but also what will be the maximum rise. Some very praiseworthy efforts have been made in this direction, but the field to be covered is large, and in order to attain that degree of success which is desirable such a study must go hand in hand with experimental work. Tests on complete transformers will not answer for this purpose, but experiments must be specifically designed to answer the questions involved, separating as much as possible the feature under consideration from all other influences. It is necessary to make a separate study of each step in the temperature gradient, determining first what conditions affect it, considered alone, and then how it is related to all the other steps. Though a large amount of experimental work and study will be involved in such an investigation, nevertheless it will be the cheapest and most satisfactory method for obtaining the desired information. The investigation may be limited, moreover, to those conditions and combinations of conditions which are practicable of application in transformer construction, when all other requirements than those of temperature rise are considered, and to those which it is thought may conduce to economy.

This paper relates to the third method of investigation described above, and though it will be impossible, at this time, to give the subject complete treatment, what follows is an effort to properly outline it, as a basis for discussion and a foundation for future work.

In passing from the hottest part of the transformer coils, or core, to the final cooling medium, for an oil-immersed transformer, the temperature gradient may be considered in seven parts, as follows:

1. From the hottest part of the coil to its surface, within the insulating covering, if the coil is covered.
2. Through the insulating covering on the surface of the coil to its outside surface.
3. From the surface of the solid insulating covering, or coil, into the adjacent oil.
4. Through the oil from a point adjacent to the coil, to a point adjacent to the tank for a self-cooling transformer, or to a point adjacent to the cooling coil for a water-cooled transformer.
5. From the oil to the metal of the tank or the cooling coil.
6. Through the walls of the tank or the cooling coil.
7. From the external surface of the tank to surrounding air, or from the inner surface of the cooling coil into the water.

These different steps cannot, however, be looked upon as definite, since the range of temperature occurring in any given step may have a wide variation for different parts of the same transformer. This condition, together with the difficulty in tracing the paths of heat discharge, and our lack of complete knowledge of nature's method of transferring heat, complicate the whole problem.

The difficulty of this problem may be better understood if we compare it with the related one of the distribution of electric potential throughout the insulating materials of the transformer. The electrostatic flux and potential in the one case are analogous to the heat flow and the temperature respectively in the other. In the problem of the distribution of potential, the potential of every portion of the windings is arbitrarily fixed. In the problem of the distribution of temperature the temperature of the windings is not fixed but must be determined. In this case the total heat flow is fixed. The difficulties of the potential problem, owing to irregular distribution of the electrostatic flux, is pretty generally understood. In the thermal problem we find similar difficulties, owing to the irregular distribution of the flow of heat. We have here, also, the added difficulty of the disturbing effect of convection currents and eddies, in the oil, and in the air, or the water, which not only modify the distribution of any given flow of heat, but also change the distribution when the rate of heat discharge changes. We have also another complication due to the fact that the flow of heat does not originate at the surface of the coil, but throughout its substance. This distributed origin of the heat, together with the distribution of thermal resistance found within the coil, affect the distribution of heat flow on the surface of the coil, and so affect the temperature distribution outside of the coil as well as inside.

It will be understood then that with this problem, even more than with the one of potential distribution, any theoretical treatment must be based upon simplifying assumptions, which are more or less at variance with the actual conditions of any particular case. For certain ideal sets of conditions these assumptions will apply approximately. Here the subject is susceptible of rational treatment, and the only experimental work required is that which is necessary for checking the theory and for determining the constants involved. In general, however, good judgment must be used in applying the rational treatment, and this can be obtained only by that close relationship between theoretical treatment and experimental work indicated above. On the one hand, theory will act as a guide in outlining the experiments, and on the other hand judgment in applying the theory, and assistance in modifying it to more nearly fit the conditions, will be obtained from the tests.

Within the range of the temperature gradient of which the various steps are outlined above, radiation, conduction and convection are all involved. It is necessary therefore to give distinct consideration to these different means by which heat is transferred.

Though much of the best talent for scientific investigation that the world has produced has been expended in the investigation of this subject, the difficulties are so great that the laws of cooling are not yet thoroughly understood. The law of direct proportionality between heat flow and temperature difference holds in the case of conduction only, and even here it is complicated by the fact that changes in temperature affect the thermal resistance of materials as well as their electrical resistance. This effect may probably be ignored however for the temperature ranges involved in transformer cooling.

The transfer of heat by conduction occurs alone in the 1st, 2nd, and 6th steps of the temperature gradient as outlined above, and in conjunction with convection in the 3rd, 5th and 7th. Where conduction operates alone, the temperature drop in the direction of the heat flow is expressed in terms of the product of the density of the heat stream, the specific thermal resistance of the material and the length of the path considered. The units used in this paper are, respectively, watts per square inch, degrees cent. per mil and per watt per square inch, and mils.

Radiation appears in our problem in the transfer of heat from the tank to the walls of the room, or surrounding objects, and also to some extent from the coils and core to the tank, since the diathermacy of oil is probably somewhere between 25 and 30 per cent. In the former case it acts, so to speak, as a shunt to step 7, and in the latter as a shunt to steps 3, 4 and 5, of the temperature gradient.

For radiation, according to the Stefan-Boltzmann law, the relation between temperatures and heat emitted is expressed by the equation:

$$R = K\,(T_1^4 - T_2^4)$$

where R is the rate of heat emission, T_1 and T_2 are the absolute temperatures of the cooling body and its surrounding objects respectively, and K is a constant, the value of which depends upon the units used. If R is expressed in watts per square inch and T_1 and T_2 in degrees cent., the value of K is, for the theoretical black surface, 3.425×10^{-11}.

This law applies accurately only to the black surface, and would lead to large errors if applied to surfaces which radiate poorly, over wide ranges of temperatures. It will probably apply with sufficient accuracy however, over the ranges of temperature in which we are interested, if we have the proper values for K to apply to the different kinds of surface. By substitution in our formula of the results from Peclet's experiments for the heat radiated from the surface at 100 deg. cent. to its surroundings at 0 deg. cent., we obtain the following values:

Ordinary sheet iron	2.275×10^{-11}
Sheet iron polished	0.189×10^{-11}
New cast iron	2.61×10^{-11}
Rusted iron	2.75×10^{-11}

Terne plate	0.535×10^{-11}
Lamp black	3.29×10^{-11}
Full radiation	3.425×10^{-11}

In considering the effect of paint, although we have no very definite information, we may draw some general conclusions from the experiments of Melloni and others on comparative radiating power at 100 deg. cent., recognizing the fact that these figures are only approximate. The following figures are found in text books on "Heat."

Lamp black	100
White lead	100
Ivory, jet, marble	93 to 98
Glass	90
Indian ink	85
Steel	17
Polished brass	7
Polished silver	3

For absorptive power the following figures are given:

	Oil lamp	Incandescent platinum	Copper 400 deg. cent.	Hot water Cb. 100 deg cent.
Lamp black	100	100	100	100
Indian ink	96	95	87	85
White lead	53	56	89	100
Shellac	48	47	70	72
Metallic surface	14	13.5	13	13

These figures indicate that the color of a pigment paint makes little difference at ordinary temperatures, although at high temperatures the lamp black radiation would be much greater than that, for instance, of white lead. With a metallic paint, however, the radiation is considerably reduced.

The importance of radiation in the cooling of transformers, or electrical apparatus in general, is often overlooked, as there seems to be a popular impression that radiation plays a small part as compared with convection. Take the case of an ordinary boiler tank, with plain surface, the total heat discharged by both radiation and convection, with a rise of 40 deg. cent. in the top of the oil, is ordinarily about 0.25 watt per sq. in. (0.04 watt per sq. cm.). The value of K for the boiler iron tank, painted, is probably not less than 3×10^{-11}. If we assume the temperature of the surrounding objects to be 25 deg. cent., and that the average temperature of the surface of the tank is 7 deg. cent. lower than the top oil, the heat lost by radiation is about:

$$R = 3 \times 10^{-11} (331^4 - 298^4)$$

$$= 0.1235 \text{ watts per sq. in. } (0.0191 \text{ watts per sq. cm.})$$

This is about 50 per cent of the total heat emitted. This proportion does not hold, however for the corrugated tank, or tank with external radiating tubes. The increased cooling with a corrugated surface is due mainly to the increase in convected heat. The radiation is not increased at all except in so far as the external dimensions of the tank are increased, since the radiation in any direction is proportional to the projection of the tank upon a plane at right angles to that direction.

With a constant room temperature of 25 deg. cent., the effect of temperature rise upon radiation, as expressed by the Stefan-Boltzmann law, is represented by the curve in Fig. 1, while the radiation for the temperature rise of 40 deg. cent., for different room temperatures, is shown in Fig. 2.

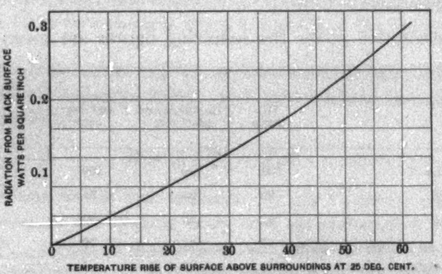

FIG. 1

The action of radiation is somewhat complicated by the fact that, though dry air is perfectly diathermous, water vapor is not, so that a varying portion of the radiated heat is absorbed in the immediate neighborhood of the tank, depending in amount upon the density of the water vapor. Although this heat has been actually discharged from the tank, by raising the temperature of the air in the immediate neighborhood of the tank, it affects the amount of heat which will be discharged by convection. A similar action takes place in the oil in the immediate neighborhood of the coils and core. The shunting action of radiation referred to above is thus somewhat modified, since a part of the heat radiated from the coils and core shunts step 3 only.

Convection plays a very important part in the cooling of transformers, by carrying the heat away from the tank, and by transporting it from the surfaces of coils and core to the tank, or to the cooling coil. Without convection the process of cooling, apart from radiation, would consist in the conduction of heat through the enormous thermal resistance of the mass of oil in the tank, and again, of the air outside of the tank.

The third step in our temperature gradient may be looked upon as one of conduction through a thin layer of oil, the thickness of this equivalent layer depending upon the velocity of the oil flow over the surface. This effect of velocity upon the thickness of the conducting layer may be the same, whether it be artificially produced, as in forced circulation, or whether it be due to the unaided action of convection. With artificial circulation and a given rate of flow the thermal resistance of this step is constant, and the temperature drop through the conduction layer is directly proportional to the density of the heat stream in watts per square inch. When, however, the circulation is that due to convection alone, an increase in the amount of heat discharged will result in an increased velocity, and hence in a reduction of the equivalent thickness of the layer of conducting oil. The thermal resistance is thus reduced with increased heat discharge, so that the temperature drop does not increase in direct proportion to the watts per square inch, but is smaller in proportion as the watts increase.

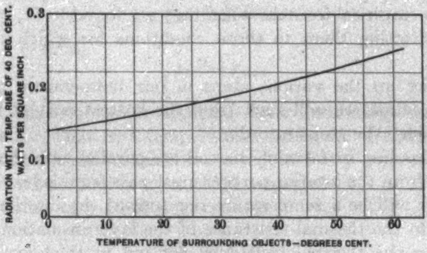

FIG. 2

The action at the inner surface of the tank, or the outer surface of the cooling coils, step 5, is very similar to that of step 3, the difference being that the heat flow is from the liquid to the solid instead of from the solid to the liquid.

Now convection alone is concerned in the bodily transportation of heat, in step 4, from the conductive layer on the coils or core to that on the cooling coils or tank. It is, moreover, as a physical fact, hopelessly involved with conduction in the third and fifth steps, and also in the seventh, in a manner which may be pictured in a general way by the imagination, but cannot be adequately expressed mathematically. Although it has been attempted to give this subject rational treatment, probably any such treatment must be based upon simplifying assumptions which are so far from the true conditions as to be of little value, and the subject can be most properly dealt with experimentally, adopting empirical formulæ when they are found to fit, but carefully restricting them to those conditions for which they are devised.

To take up the various steps in our temperature gradient more in detail, we will start from the hottest part of the coil, and consider the steps in order.

If the cooling surfaces of the coil are parallel with the layers, the heat from the interior portion must pass from layer to layer, and there will be a temperature rise toward the interior of the coil due to the thermal resistance of the layer insulation.

Let ρ = the thermal resistance per mil in thickness of one square inch of the layer insulation expressed in deg. cent. with one watt per square inch flowing.

Let i = the thickness of insulation between layers in mils.

Let q = the watts generated in one square inch of each layer.

Let n = the number of layers of conductors from the hottest part of the coil to its surface, whence

$n - 1$ = the number of layers of insulation, if there is no layer of insulation over the outside layer.

Now the temperature rise of the second layer from the outside above the temperature of the first is $q\,i\,\rho\,(n-1)$, that of the third above the second, $q\,i\,\rho\,(n-2)$ etc., to the hottest layer, whose temperature rise above the one next to it is $q\,i\,\rho$. The temperature rise of the hottest layer above the temperature of the outside one is, therefore,

$$t_{max} = q\,i\,\rho\,\frac{n^2 - n}{2}$$

$$= q\,i\,\rho\,(n-1)\,\frac{n}{2}$$

If the coil cools equally in both directions, or all in one direction, the average temperature rise of the coil above the temperature of the surface layer will be

$$t_{av} = q\,i\,\rho\,(n-1)\,\frac{2\,n-1}{6}$$

If n is large, this is practically

$$t_{av} = q\,i\,\rho\,(n-1)\,\frac{n}{3}$$

so that

$$t_{av} = \tfrac{2}{3}\,t_{max}.$$

When n is small

$$t_{av} > \tfrac{2}{3}\,t_{max}.$$

The values of ρ for ordinary layer insulating materials is about 0.3. That is, a temperature, difference of about 0.3 deg. cent. for each mil in thickness is required to force one watt per square inch through a layer of the material.

The value of q at 25 deg. cent. is

$$q = 0.6935 \times 10^{-6}\,c\,s\,D^2$$

where $c =$ the thickness of the layer of conductors $s =$ the space factor in the layer and $D =$ the current density in amperes per square inch.

At 75 deg. cent. this value would be

$$q = 0.825 \times 10^{-6}\,c\,s\,D^2$$

If we substitute the value of q in the formulæ for temperature rise, inspection shows that the rise is proportional to the square of the current density, and to the thickness of the layer of conductors, and that it is approximately proportional to the square of the number of layers where the number of layers is large, being greater in proportion for smaller numbers of layers.

If we consider the effect of changing the size of the conductor for a given transformer without changing its shape, or the number of layers, we have:

$$c = \text{Const.} \times \frac{1}{D^{\frac{1}{2}}}$$

whence the temperature rise is proportional to the $\frac{3}{2}$ power of the current density. If the thickness of the conductor remains constant, its width in the layer being varied, the temperature rise is proportional to the square of the current density, since c does not change. If the width of the conductor remains constant, we have

$$c = \text{Const.} \times \frac{1}{D}$$

so that the temperature rise is directly proportional to the current density.

If the cooling surfaces are at right angles to the layers, the heat is discharged from turn to turn in the layer instead of from layer to layer. Since the turn insulation is ordinarily much thinner than the layer insulation, the temperature rise within the coil, for given thickness and current density, will be much smaller in this case. It may be calculated in the same manner, but if the turn insulation be of cotton covering, the value of ρ in this case will be smaller since the thermal resistance of the impregnated cotton is smaller than that of the materials ordinarily used for layer insulation.

The temperature rise of the outer layer of the coil above the temperature of the outer surface of the insulating covering depends upon the same principles as those controlling the temperature rise within the coil. This temperature rise is

$$\tau = q\, i\, \rho\, n$$

Comparing this temperature rise through the insulating covering with the average temperature rise within the coil, for a coil with a large number of layers, it is seen that with an insulating covering of the same thickness as the layer insulation, and with the same specific thermal resistance, this rise is the $\frac{3}{n-1}$th part of the average interior rise. Thus the temperature rise through the covering is three times as great as the average interior temperature rise divided by the number of layers of insulation, or the insulating covering needs only to be $\frac{n-1}{3}$ times as thick as the layer insulation to make the temperature drop from the outside layer through the insulating covering as great as the average rise of the coil above the temperature of the outside layer.

The above discussion is based upon the assumption that the total heat flow is perpendicular to the cooling surface considered. This condition is approximately fulfilled in the case of a long cylindrical coil mounted vertically, the turns of the conductor being in a horizontal plane, although in this case the ends of the coil will be somewhat cooler, owing to the heat which passes out at the ends. Also, if the temperature of the oil adjacent to the top portion of the coil is much higher than at the bottom, there will be a tendency to transmit heat downward in the coil. The heat so transmitted will be small, however, since the thermal resistance is high as compared with the temperature difference in this direction. The most important result will be that the temperature of the top portion of the coil will be almost as much higher than the temperature of adjacent oil as that of the bottom portion is above the oil adjacent to it. This, of course, assumes that the equivalent thermal resistance from the coil to the oil is practically uniform throughout the length of the duct. The total average temperature of the coil is therefore related by the equations given, with sufficient approximation, not to the surface temperature at the bottom of the coil, but to a temperature which is average for the entire surface, which may be considerably higher than that at the bottom; also, the maximum temperature at the top of the coil may be considerably higher than the maximum calculated by the formula from this average surface temperature, and should be calculated from the surface temperature near the top of the coil.

We come now to the most difficult part of the whole problem, with natural oil circulation, namely, the distribution of temperature through the oil, from the solid surface of the coil to the surface of the tank, or cooling coil. The dependence of the equivalent thermal resistance from the surface of the coil to adjacent oil upon the velocity of the oil has already been pointed out. For a given velocity this resistance is constant, the temperature drop from coil to oil being directly proportional to the watts per square inch discharged from the coil. This is true also of the temperature rise in the oil as it passes through the duct. Thus, with forced circulation, returning the oil to the ducts at a definite temperature, the whole problem is simplified, the only lacking element being a definite knowledge of the relation between the equivalent thermal resistance at the surface of the coil, and the velocity of the oil.

With natural circulation the oil flow is caused by the difference in temperature between the average temperature of the oil inside the duct and that of the outside oil, between the levels of entrance to and exit from the duct. The head producing this circulation is

$$h = \gamma L (\theta_{av} - \theta_{av}')$$

where γ is the coefficient of expansion of oil L is the length of the duct and θ_{av} and θ_{av}' are the average temperatures inside the duct and outside the duct respectively, these temperatures being measured from the temperature at the bottom of the duct. This head is consumed almost entirely by friction, since the velocity head is negligibly small. If the friction of oil is directly proportional to the velocity, and inversely proportional to the length of the duct, we may write

$$V = \frac{\text{const.} \times \gamma L (\theta_{av} - \theta_{av}')}{L}$$

$$= \text{const.} \times \gamma (\theta_{av} - \theta_{av}')$$

If we call the specific heat of oil 0.434, and its density 0.875, the temperature rise of the oil during its passage through the duct, where heat is discharged into one side of the duct only, is

$$\theta_{max} = \frac{n q L}{26 V d}$$

where d is the thickness of the duct. If heat is discharged into both sides of the duct this will be

$$\theta_{max} = \frac{2 n q L}{26 V d} = \frac{n q L}{13 V d}$$

Substituting for V, this becomes

$$\theta_{max} = \frac{n q L}{13 \times \text{const.} \times \gamma (\theta_{av} - \theta_{av}') d}$$

For the cylindrical coil which turns in a horizontal plane,

$$\theta_{av} = \tfrac{1}{2}\,\theta_{max}.$$

If we have a diaphragm separating the oil in contact with the tank from that in contact with the outside coils of the transformer, the temperature of the oil adjacent to the tank, plotted up the side of the tank, will be a straight line, so that

$$\theta_{av}' = \tfrac{1}{2}\,\theta_{max}'.$$

Now in order that circulation may occur θ_{av}', must be less than θ_{av}, whence θ_{max}' must be less than θ_{max}. This is accomplished by the mixing of the hot oil leaving the duct with other oil which has been cooled by contact with the tank. We find that this mixing results in a practically uniform temperature of oil from the top of the transformer to the top of the oil, which is practically the temperature θ_{max}'. The result is that the difference between θ_{max} and θ_{max}' tends to become greater, the greater the distance from the top of the transformer to the oil level, with a resulting increase in the velocity of circulation, which reduces the temperature drop from the coils into the oil, and results in a smaller value for both θ_{max} and θ_{max}', although their difference is greater. The temperature at the bottom of the duct is raised, while that of the oil above the transformer is lowered. Whether or not the average temperature of the windings will be lower for a tall tank than for a short one, with given average oil temperature, it is certain that the maximum temperature at the top of the coils and the temperature of the oil at the top of the tank will be lower, the temperature distribution being more uniform from bottom to top throughout the transformer.

If there is no diaphragm between the outside coils and the tank, the temperature of the oil adjacent to the tank, from the top of the transformer downward, will fall away less rapidly at first, but will come down more rapidly with a curve toward the bottom. In this case θ_{av}' is greater than $\tfrac{1}{2}\,\theta_{max}'$. and the velocity of circulation through the ducts will therefore be reduced, causing a higher temperature rise in the oil passing through the ducts, and also a greater drop from the surface of the coil to adjacent oil.

The effect of the thickness of the duct upon temperature rise will be very different for forced circulation than for natural circulation. With forced circulation a thin duct will be better than a thick one, since the resulting higher velocity of the oil will give smaller temperature drop from the surface of the coil to the oil. With natural circulation a thick duct will give practically the same condition as to temperature rise as that obtained on an external surface, the rise being less than for a thin duct. Thinning the duct does not, however, cause as great an increase in temperature rise as might be expected, up to a certain point, since, though the temperature rise of the oil while passing through will be greater, this temperature rise tends to produce a higher velocity, and hence to cause a smaller drop from the coil into the oil, as well as to reduce the net temperature rise in the oil itself. When the duct becomes too thin, however, a point is reached where friction becomes serious, so that the curve of temperature rise in the windings, as the duct becomes thinner passes from a flat one to a steep one, probably with rather a sudden deflection. The economy of design resulting from the thin duct makes it desirable that the duct should be as thin as may be, and yet stop short of the steep part of this curve.

The discharge of heat into the duct from both sides, as compared with its discharge from one side only, is an important matter in connection with cooling. It is found that with a duct of given thickness, if the heat is discharged into it from both sides, at a given density in watts per square inch, both the temperature rise of the oil while passing through the duct, and the temperature rise of the coil above adjacent oil, will be smaller than if the heat is discharged into one side of the duct only, at the same density. Thus twice the heat is carried away by the duct, with a smaller temperature rise.

The smaller temperature rise of the oil while passing through the duct, though absorbing twice the heat, indicates that the velocity of flow is more than double, and this accounts for the reduced drop from the coils into the oil. The great difference in velocity in the two cases is accounted for by the friction on the side of the duct where no heat is discharged, which is much greater than when heat is being discharged.

We have so far considered our subject only in connection with coils in which the turns are in a horizontal plane. In shell-type transformers with vertical oil ducts between flat coils, in which the conductors are parallel to the ducts in a vertical direction, conditions are quite different. With the type of winding common in these transformers, the layer insulation is not in the path of heat flow, and the insulating covering is thin, so that the first important step in the temperature gradient is that spoken of above as step 3, in going from the solid surface to the liquid oil. The equivalent thermal resistance of this step is uniformly distributed throughout the length of the duct, since the rate of oil flow is the same throughout, but this resistance will change with changes in the rate of heat discharge because the velocity of the oil will be different. Now if the heat generated in any part of the coil were all transmitted directly to the oil through that part of the surface which is opposite, the oil would receive heat at a uniform rate throughout its passage through the duct, and the difference between the temperature of the coil and that of the oil would be the same at the top as at the bottom. The temperature at the top part of the coil would therefore be as much greater than its temperature at the bottom as the temperature of the oil leaving the duct is greater than its temperature at entrance. This would result in the passage of a considerable portion of heat downward through the copper, which is a good conductor of heat. This actually takes place, with the effect that more heat is discharged per square inch from the bottom part of the coil than from the top. The temperature rise of the oil in its passage through the duct is, therefore, more rapid in the bottom portion of the duct than in the top, and the temperature drop from the coil to the oil is also greater in the bottom portion of the duct than in the top, on account of the greater density of heat flow. The temperature gradient in the copper from the top of the coil to the bottom is thus reduced, giving a more uniform temperature, as well as a lower average temperature. On the other hand, though the temperature of the oil where it leaves the duct would be the same, if its velocity were the same, since it absorbs the same total heat, yet its average temperature throughout the duct will be greater on account of the larger proportion of heat which it receives near the bottom. This will result in an increase in the velocity of circulation, which tends to reduce both the temperature rise of the oil in the duct and the temperature drop from the coil into the oil, both of these actions affecting further reduction in the temperature of the coils.

We have another important practical case for consideration in connection with the use of disc shape coils, assembled in a horizontal position, with horizontal ducts between. These coils may be wound either in single turn layers, or with several turns per layer. In the former case practically all the heat will be thrown out into the horizontal ducts, but in the latter the inner and outer layers will discharge considerable heat through layer insulation to the inner and outer cylindrical surfaces. A large portion of the heat will, however, find an easier passage out through the horizontal oil ducts than from layer to layer in the coil. The relative amounts passing out through the two paths will depend upon the circulation of the oil. If the oil is stagnant in the horizontal ducts, it reaches a temperature where it ceases to absorb heat. This condition can only be partial, however, since there is always a tendency for the hot oil to leak out from these ducts, its place being taken by cooler oil.

This type of winding is attractive from the standpoint of design, since if the cooling surface obtained in this manner is sufficiently effective it will give the necessary cooling surface more economically than where this surface must be obtained by unduly lengthening the coils and core in a vertical direction. The relative effectiveness of this method of cooling must be determined by experimental means, the tests covering such points as the effect of the thickness of the horizontal ducts, the presence or absence of internal or external vertical ducts, etc.

The core will not need separate consideration with respect to temperature steps 1, 2 and 3, except to state that the thermal conductivity of iron is such that the interior temperature rise is small, and that, in considering the temperature drop at the surface, we must distinguish between the surface which exposes the edges of all the laminations to the oil, and that which exposes but a single lamination. The relative amounts of heat discharges from these two surfaces, and consequently the magnitude of the temperature drops from the respective surfaces to the oil, will depend somewhat upon the relative thermal resistance in the two directions within the core.

The fifth step in the temperature gradient bears a relation to the density of the heat current and the velocity of oil flow which is similar to that of step 3. The temperature drop from the oil to a surface which is absorbing heat from it, is reduced by forced circulation over this surface in a manner similar to the reduction in temperature drop from the coils to the oil with forced circulation, which has already been described. This involves a comparatively thin duct adjacent to the cooling surface through which the oil must pass.

Before leaving the general subject of the behavior of oil in the process of cooling the transformer, the influence of viscosity should be pointed out. An increase in the viscosity of the oil means an increase in the frictional resistance to its flowing. It results, therefore, in a reduced velocity of circulation, thereby causing an increased drop from the coils and core into the oil, an increased rise in the temperature of the oil while flowing through the ducts, and an increased drop from the oil to the tank. The net result is a higher temperature of the oil at the top of the tank, though its temperature may be lower at the bottom, and a higher temperature in the windings.

The sixth step of the temperature gradient is negligibly small, being due only to the thermal resistance of the metal in the tank. It need not have been mentioned in this discussion except for the fact that something occurs here which often assists very materially in cooling. The top of the tank usually extends several inches above the oil level, while at the bottom of the tank several inches of stagnant oil is usually found, which is practically cold. The tank, especially if of heavy material, as with cast iron, conducts considerable heat upward at the top, and downward at the bottom, thus increasing the area of the external cooling surface. The importance of a given percentage of increase in this surface is all the greater because of the magnitude of the temperature drop from the tank surface to the air.

The seventh step in the temperature gradient, from tank to air, is most important of all, because it is much larger than any of the others. In seeking for engineering economies, the larger items deserve the more careful attention. This step is, therefore, worthy of most careful study.

It has been pointed out above that about half of the heat discharged from a plain tank is thrown out by radiation. Since radiation depends upon the external dimensions of the tank, and not upon its developed surface, the increased cooling obtained with corrugations, cooling tubes, etc., is due to the increase in convection only. This explains why a corrugated surface is so ineffective as compared with a plain one, inch for inch. Comparing a plain tank with a corrugated one of equal dimensions, but with four times the developed surface, if all parts of the corrugated surface are equally as effective for convection as the plain surface, and if 50 per cent of the heat thrown out from the plain tank is convection and 50 per cent radiation the total heat thrown out by the corrugated tank will be 50 per cent × 4 plus 50 per cent = 250 per cent of that thrown out by the plain one, so that the watts per square inch thrown out by the corrugated tank, at the given temperature, are $\frac{250}{4} = 62.5$ per cent of the watts per square inch from the plain one, and the radiation from the corrugated tank is $\frac{50}{2.5} = 20$ per cent of the total heat thrown out.

This result is better than can be expected from a corrugated tank, since in order that all parts of the surface may be equally effective for convection, an equal amount of air must be supplied to every element of surface, to the depth of heat penetration. In order that this may be approximately true for a corrugated surface, the corrugation must be wide and deep, rather than narrow and shallow. Thus with the same outside dimensions, and the same developed surface, the tank with large corrugations will throw out more heat than the tank with small ones, first, because the corrugations contain more air, and second, because the velocity of the air will be smaller in the smaller corrugations on account of the greater friction. And besides the reduced amount of air for absorbing the heat, we probably have here also, as in the oil, an additional increase in the equivalent thermal resistance due to the decreased velocity.

The relative space required for oil and air within the corrugations of a cooling tank is an important consideration. The relative thermal capacities, and densities, of oil and air, easily convince one that the space allowed for air should be large as compared with that allowed for oil, since the product of the thermal capacity and density of oil is many times that of air. Actual measurements show not only that the temperature drop from the oil to the tank is very much smaller than that from the tank to the air, but also that it occurs within much smaller range of the tank. In order to avoid undue effects from friction, however, oil ducts in which heat is discharged by the oil should be more generous than those between the coils, where the oil is absorbing heat.

If they receive the attention which they deserve, each of several phases of the subject which we have outlined will afford material for a lengthy and valuable paper.

Definite figures for the relative values of the various steps of the temperature gradient have not been given since these depend upon the specific conditions of each particular case. It is hoped, however, that the discussion may bring out much definite information, and that this paper may serve as a nucleus for future contributions.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

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DISSIPATION OF HEAT FROM SELF-COOLED, OIL-FILLED TRANSFORMER TANKS

BY J. J. FRANK AND H. O. STEPHENS

This paper is confined to a presentation of the relative merits of the most commonly used designs of tanks for self-cooled transformers. However, since any tank, in addition to dissipating the heat, must fulfill the following requirements, no consideration has been given to discussion of impractical constructions.

In addition to diffusing the heat, a satisfactory tank should, first, be absolutely oil-tight; second, should be of good mechanical construction; third, should occupy small floor space; fourth, should be symmetrical; fifth, should be inexpensive.

Heat is diffused from the surface of self-cooled, oil-filled transformers by three ways; by conduction, by convection, and by radiation. The oil receives its heat from the transformer itself, transfers it to the inner surface of the tank by convection currents, where it is transmitted through the metal to the outer surface of the tank. The ease with which both the oil and the air circulate along the surfaces of the tank contributes to the diffusion of the heat. In addition to the diffusion by the convection currents of air, heat is diffused by direct radiation, and also by conduction from the tank to its support.

The amount of energy that may be dissipated from a tank for a given temperature rise of oil depends upon the extent and nature of the surface exposed to the air. A plain surface per unit of area is the most efficient as the air and oil come in closer contact with it. As the volume or capacity of a transformer varies as the cube of its dimensions, and the surface as the square of its dimensions, the use of a smooth surface for dissipating the heat in a transformer must therefore be confined to transformers of small capacities involving low losses. Where large capacities and great losses are involved special provision for radiation must be made. The greater the loss, the more complicated the provision naturally becomes.

Various methods have been used to increase the radiating surface of tanks without too greatly increasing the size and cost. A general classification is outlined as follows:

1. Smooth surface.
    - (*a*) cast iron or cast steel.
    - (*b*) wrought iron or rolled steel.

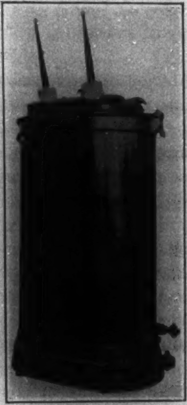

FIG. 1.—Plain cast iron tank

FIG. 2.—Plain boiler plate tank

2. Ribbed surface.
    - (*a*) cast ribs.
    - (*b*) attached ribs.
3. Corrugated surface.
    - (*a*) simple.
    - (*b*) compound.
4. External pipes or radiators.

1. Tanks with smooth surfaces having no special provision for radiation are suitable for self-cooled transformers only when the dissipation of small losses is involved. Due to the roughness

of the surface, cast iron will radiate more heat than rolled plate since the roughness increases the surface exposed to the air and oil. In general, the metal in a cast tank is thicker and therefore conducts more heat above and below the band of hottest oil. Fig. 1 shows a plain cast iron tank, and Fig. 2 a plain boiler plate tank.

2. The simplest method for increasing the radiating surface is to attach ribs to the tank. Fig. 3 shows a tank of this type. Wrought iron strips are set on edge at intervals of about one in. (2.54 cm.) around the circumference of a plain, cylindrical, boiler plate tank, and are clamped tightly against it. The strips conduct heat from the tank at their bearing surfaces, and air, passing up along them, carries away their heat, and also the heat from the tank surface between the strips. One objection to this construction is the difficulty of obtaining a good contact at the bearing surfaces of the strips and tank, so that the effectiveness of the strips is always somewhat indefinite. In a cast tank the ribs are an integral part of the tank and are hence more effective. They are sometimes cast both on the inner and outer surface of the tank. In either case, the height and thickness of the ribs should be accurately determined, or the weight may be un-

Fig. 3.—Boiler plate tank with attached ribs

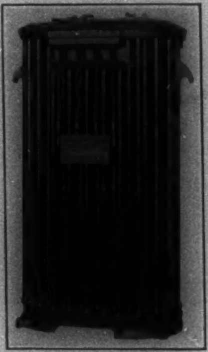

Fig. 4.—Corrugated cast iron tank

necessarily increased, because it is possible to have quite a difference of temperature between the outside edge of the ribs and the surface of the tank if the ribs are not properly proportioned.

3. The most generally used method for increasing the periphery of a tank is to corrugate or flute the surface. By this means, the surface may be increased to several times that of a plain tank of the same over-all dimensions. Tanks of this type may be either of cast iron or of sheet metal. Fig. 4 shows a corrugated cast iron tank, and Fig. 5 gives the dimensions of its corrugation.

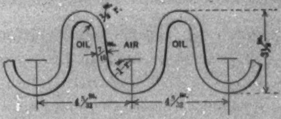

FIG. 5

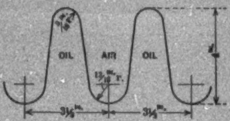

FIG. 7

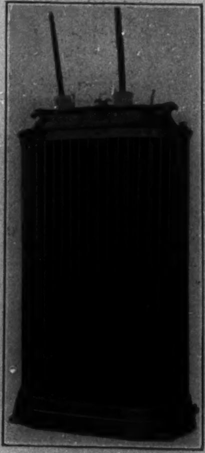

FIG. 6.—Simple corrugated steel tank

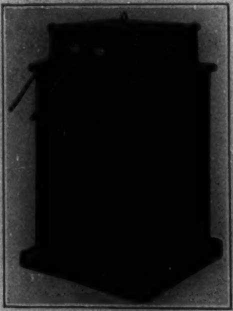

FIG. 8.—Corrugated steel tank—*V* corrugations

Figs. 6 and 7 show a form of corrugated steel tank very commonly used. By referring to Figs. 5 and 7, it will be noted that the space within the corrugations occupied by air is greater than the space occupied by oil. Figs. 8 and 9 show a corrugated steel tank with simple V corrugations with equal spaces for air and oil. Figs. 10 and 11 show a tank with rectangular corrugations.

A large number of modifications of these forms of corrugations have been used, but, as the capacities of transformers become larger, and the losses high, it becomes expedient to adopt more complicated surfaces in order to keep down the size and cost of the tanks. A recent and important development along this line is a tank with compound corrugations. It is obtained by double-corrugating the surfaces so that it will be made up of major and minor corrugations. The minor corrugations may be similar to the preceding illustrations and the major corrugations are made up of a number of the minor corrugations.

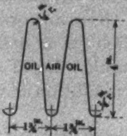

FIG. 9

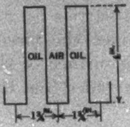

FIG. 11

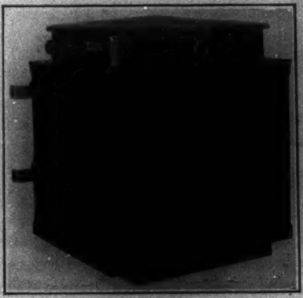

FIG. 10.—Corrugated steel tank—rectangular corrugations

FIG. 12.—Boiler plate tank—external radiating pipes

4. Examples of another scheme coming into practice are shown in Figs. 12 and 13. These tanks have auxiliary pipes or radiators apart from the transformer tank proper. Fig. 12 is a cylindrical

boiler-plate tank with external radiating tubes, and Fig. 13 is a large corrugated steel tank with external corrugated cooling boxes. Hot oil enters the auxiliary pipes at the top, cools and sinks to the bottom. The method does not differ materially from the ordinary tanks, excepting the definite path provided for the circulating oil. Fig. 14 shows the circulation in an ordinary tank with a barrier between the transformer and the tank wall. This confines the circulation to a definite path down along the cooling surface of the tank. Local eddy currents in the oil are thus avoided and the circulation is much more effective.

The curves in Fig. 15 were plotted from a large number of tests made to determine the oil temperature rise at various losses for different kinds of tanks. They show the relation between the temperature rise of the oil at the top of the tank and the watts loss per square inch of tank radiating surface. The oil temperature rise of a transformer may be determined by means of these curves when the losses are known and the radiating surface of the tank has been calculated. The radiating surface used for these curves consists of the total wetted surface of the tank exclusive of the bottom, since the radiation from the bottom would be extremely small in any case. The actual radiating surface of a tank varies with the temperature of the oil, since the oil expands with the heat, and rises higher in the tank, thus increasing the effective surface. For uniformity, the oil level at 25 deg. cent was used for calculating the radiating surface and the curves take care of the differences due to oil expansion.

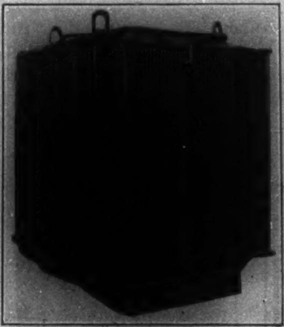

FIG. 13.—Corrugated steel tank—external radiating boxes

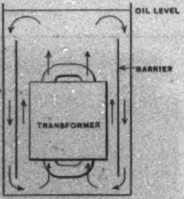

FIG. 14

The oil temperature curves in Fig. 15 may be expressed by an equation of the following form:

$$T=K\,W^{p}$$

in which T is the temperature rise above 25 deg. cent., W is the average watts per square inch of tank surface, and K and p are constants depending upon the form and material of the tank and the conditions of the test.

All of these curves were plotted with the watts per square inch corresponding to the actual losses in the transformers at the operating temperatures.

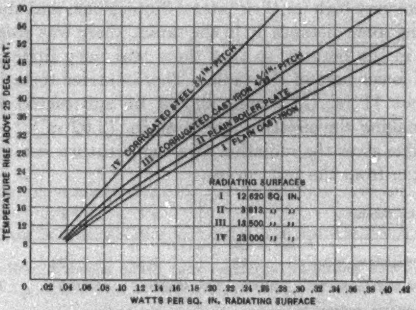

FIG. 15.—Maximum oil temperature rise for transformer tanks

The dimensions of these tanks are given in the table.

	Thickness of metal	Floor space	Height	Radiating surface	Illustrations
Plain cast iron....	½ in.	5 ft. 2 in. by 3 ft. 4 in.	7 ft. 7 in.	12620	Fig. 1
Plain boiler plate..	¼ in.	2 ft. 9 in. by 1 ft. 9 in.	4 ft.	3813	
Corrugated cast iron	7/16 in.	3 ft. 7 in. by 2 ft. 4 in.	6 ft. 8 in.	13500	Figs. 4 & 5
Simple corrugated steel............	1/16 in.	4 ft. 5 in. by 2 ft. 11 in.	6 ft. 5 in.	23000	Figs. 6 & 7

The curve in Fig. 16 gives the results of tests on the tank shown in Fig. 12. The radiating surfaces of the pipes and the tank proper are given on the curve.

Comparative tests on a number of tanks with attached ribs similar to the one shown in Fig. 3 indicate that the rise of a tank is about 20 per cent lower with the ribs than it is without them. For example, if a plain tank runs at 50 deg. rise, it may be made to run at 40 deg. rise, with the same losses by attaching ribs to it, similar to Fig. 3.

A number of tests were made upon four special tanks having the same over-all dimensions but with different pitch of corrugations. The depth of the corrugation was 4 in. (10.16 cm.) for each tank. Unlike the corrugations in the previous tests, the space occupied by oil and air within the corrugations was equal. The lateral dimensions of the tank to the outer portion of the corrugations was 39½ by 39½ in. (one m. sq.). The height was 8 ft. (2.43 m.) and the oil level 5 in. (12.7 cm.) below the top, making the height of the wetted surface 91 in. (2.2 m.). These tanks were very high for their lateral dimensions, and the heating units being some distance up in the tanks, there was considerable dead oil in the bottom, so that there was very little radiation from the lower part of the tank. Thermometer tests indicated that about 11 in. (27.9 cm.) should be subtracted from the height, making the effective height 80 in. (2.02 m.).

The table gives the radiation at a temperature rise of 40 deg. cent. taken from the test curves.

Tank number	1	2	3	4
Pitch of corrugations, in......	1¾	2.1	2⅝	3.50
Total wetted surface, sq. in...	56,900	48,300	39,200	30,300
Effective radiating surface, sq. in..........................	50,000	42,500	34,500	26,600
Kw. radiated at 40 deg. cent. rise........................	5.8	5.43	5.13	4.85
Apparent watts per sq. in.....	0.102	0.112	0.131	0.160
Watts per sq. in. effective....	0.116	0.128	0.149	0.182

The tests indicate that the gain in radiation to be obtained by reducing the pitch of the corrugations so as to increase to total surface is entirely disproportionate to the increase in surface. While tank No. 1 has a radiating surface 88 per cent greater than tank No. 4 it radiates only 19.6 per cent more losses at 40 deg. rise in the oil. The following conditions combine to cause this:

For two tanks of the same dimensions, the increase in surface obtained by closer corrugations has no effect upon direct radiation, so this component of radiation remains unchanged.

Air flowing in at the bottom of the corrugations receives heat from the tank and passes up through the corrugations with an increasing velocity as its temperature rises. More air must flow in at the side along the corrugations to make up for this increased velocity. If the corrugations are pressed closer together so that the ratio of air space to radiating surface is smaller, the air would have to flow at a greater velocity to carry off the same watts per square inch. Air friction varies as the cube of its velocity and hence it will not flow at a sufficient velocity to carry off the same watts per square inch from the closer corrugations.

In addition to the causes outside of the tank, the oil will not circulate as freely over a closely corrugated surface because of the increased friction, but the effect within the tank is much smaller than it is without, principally because the temperature drop from the oil to the tank is much smaller than from the tank to air.

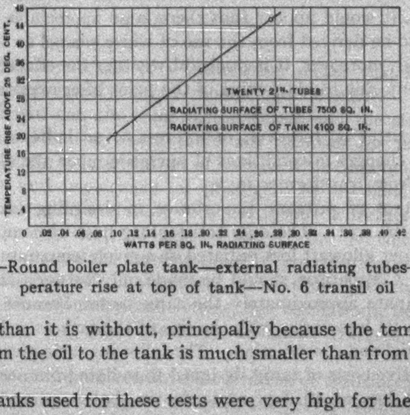

Fig. 16.—Round boiler plate tank—external radiating tubes—oil temperature rise at top of tank—No. 6 transil oil

The tanks used for these tests were very high for their lateral dimensions, and experience indicates that narrow and deep corrugations may be used to a greater advantage on lower tanks, principally because the air currents will not have to acquire such high velocities.

A principle that is suggested by the foregoing discussion is that the most effective corrugation will not have equal oil and air spaces but the air space will be much greater than the oil space. This idea has been used in the design of transformer tanks for a number of years. It has the further advantage of reducing the oil required.

It was stated in the beginning that the nature of the radiating surface has an effect upon its radiating properties. This was shown in the tests on the cast iron and the boiler plate tanks.

In addition to the material itself, the color and character of the paint has some effect upon the radiation of tanks, especially when they are exposed to the direct rays of the sun. A number of tests were made to determine whether or not this effect was appreciable. The tests were made on transformers sizes 5 to 50 kilovolt-amperes, with tanks painted with black, white enamel, and aluminum paint, respectively. The transformers were so placed that tanks were exposed to the direct rays of the sun all day long and tests were made only in clear weather.

The results of these tests indicate that tanks painted with white enamel or aluminum paint run several degrees cooler in the daytime and slightly warmer at night than tanks painted with black paint. Inasmuch as such transformers are usually loaded at night, it would appear that there is no appreciable practical benefit to be derived from the use of white enamel or aluminum paint and, moreover, it is doubtful whether the effect would be permanent, due to blackening of the paint after exposure to the weather.

The matter is, however, of interest as an indication of the effect of changes in conditions of operation upon the dissipation of heat from transformer tanks.

One item of primary importance in designing transformer tanks is the cost. The only satisfactory basis of comparison is the cost per kilowatt loss radiated at a given temperature rise of the oil. Comparison should be made only between tanks that will dissipate approximately the same losses, because the cost per kilowatt loss varies with the size of the tank as well as with its material and construction. The following table gives average comparative costs of tanks designed to radiate from one to three kilowatts loss at 40 deg. cent. rise in the oil, plain cast iron tanks being used as the standard of comparison:

Plain cast iron	100
Plain boiler plate	97
Corrugated cast iron	93
Corrugated steel	61

The above figures do not include the cost of oil and if this were added the difference in cost between the plain and corrugated tanks would be greater.

For larger losses a similar comparison would show an increased advantage in favor of the corrugated steel tank, and other more complicated surfaces, and if the losses are still further increased the plain tank becomes quite out of the question.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February. 15, 1911.

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PROBLEMS IN THE OPERATION OF TRANSFORMERS*

BY F. C. GREEN

The slightest puncture of a transformer means that it must be dismounted entirely before repairs can be made. The oil must be drawn out, the leads disconnected, and the structure moved to a location where there are facilities for hoisting. Moreover, there is interruption of service with consequent loss of revenue and impairment of prestige. At its best, transformer repairing in a station does not inspire a feeling of enthusiasm for the electrical arts. And yet the damaged coils with their slime are the starting point of progress along manufacturing lines, as well as of progress along those lines that lead to the consideration of electric stress, line oscillations, temperature gradient, and other similarly advanced features of the science.

Thus, the main problems in the operation of transformers are to select those best designed to meet the service requirements and to give them such care in their installation and such attention in service as will minimize liability of unnatural weakness or abnormal strains. Important problems arise in the adaptation of transformers to a variety of service.

INSTALLING

The high voltages used now make necessary a large amount of solid insulation between high-tension and low-tension coils and between coils and laminations. The present manufacturing practice calls for solid insulating materials that are fibrous. These cannot be so treated that they will not absorb at least a small amount of moisture from the air during shipment or storage. Occasionally, facilities for handling transformers at the station where they are to be installed, admit of shipping with the oil in them, but as a rule the transformers and oil must be shipped separately. Hence the necessity for drying arises.

The full effect of the process used should extend to the fibrous insulating materials as well as to the coils. In fact, a coil has to withstand normally a voltage not exceeding 6000 or 7000 volts and usually the voltage is much lower than this, while the voltage between windings may reach a normal value of 100,000 volts in modern transmission systems. Furthermore, coils are more easily dried than the insulation between windings. The usual short-circuit run heats the coils but the effect does not extend through the heavy insulating shields, because the heat is carried up by the air circulating through the spaces between the coils and shields, and is given up to the cover and tank. The circulation of large quantities of heated air is an easy and effective process of drying. Where the tank is suitably constructed, the vacuum process of treating the transformers filled with oil, may be used. In this case the heat must be so applied as to maintain a uniform temperature of oil throughout the tank, and the degree of temperature and of vacuum must be so related as to cause the moisture to vaporize. Unevenness of temperature makes ineffective the vacuum process of drying without oil in the tank.

Oil may be dried by blowing heated air through it or by holding it at a temperature that will vaporize moisture, either at atmospheric or a lower pressure, such as is obtained in the vacuum process. The adaptation of the filter press with blotting paper to the treatment of oil, has proved to be most satisfactory. There is no danger of injury from excessive temperature, and both the moisture and sediment are removed. In case it should be found desirable, oil may be treated by means of the filter press without taking transformers out of service.

Causes of Failures

If a high-voltage transformer is built with a safety factor of ten instead of the usual factor of two, it avails nothing in case of neglect to properly install it, assuming it to have become moist in shipment. It is equally true that this same transformer, being properly installed, is about as likely to break down as the one with the safety factor or two. This brings up a consideration of the parts of the transformer most exposed to effects of conditions that practice has shown to be dangerous. Abnormal voltage conditions are responsible for almost all transformer failures. Examination of the damaged portions has shown that it is not the total abnormal voltage impressed that is dangerous, but that the disturbance of the voltage equilibrium within the windings is responsible for a large majority of the operating troubles attributable to transformers. Thus, the percentage of punctures between high-tension and low-tension windings, or between the windings and laminations, is negligible as compared with the percentage of punctures between turns, or between portions of the same winding.

The standard practice for the potential test of high-voltage transformers is to apply twice the rated high-tension voltage between the high-tension winding and the low-tension connected to the iron. The induced voltage test is the application of twice the rated voltage to one of the windings. The purpose of the induced voltage test is to determine whether the various portions of a given winding are properly insulated from one another. This test of course subjects adjacent turns to twice the normal voltage between turns, but, as will be seen, this does not mean much except in cases of mechanical defects, which are rare.

Assume that a 100,000-volt transformer for transmission service has a normal turn voltage of 60 volts. The value of the test voltage between the high-tension winding and other parts, is 200,000 volts. To break down the transformer under this test would require, say, between 220,000 volts and 250,000 volts. Under the induced voltage test, the voltage between turns is 120 volts. But the voltage required to puncture the insulation between turns, is found to be around 5000 volts. Nevertheless, as previously pointed out, almost all failures of transformers of this kind occur between turns. Thus in the operation of transformers it is found that the designer must attempt to meet the difficult problem of taking care of a voltage between turns that may range from 60 volts under normal conditions to 5000 volts and above under abnormal conditions of line disturbances, that may not appreciably increase the line voltage, but that affect the equilibrium of the voltage within the winding to the extent of concentrating a very excessive potential across a small percentage of the total turns.

While modern lightning arresters successfully limit to a safe value the voltage between phases, and between the line and the ground, they are not adapted to the protection of the transformer against the concentration of a dangerous voltage upon a small percentage of the total winding.

The portions of the winding most liable to excessive voltages of this kind are towards the line ends; but this is not always the case, the relative location of the danger portion depending upon the nature of the disturbance of the voltage equilibrium. However, the percentage of transformer failures is small; but there is reason to believe that it can be reduced to an inappreciable value by means of increasing the effective insulation between parts of the winding most liable to damage, and by means of reducing line disturbances to a practicable minimum. Also, the transformer is less liable to the effects of line disturbances where its capacity in microfarads is small.

Another cause of destruction of transformers is their connection to bus bars of generators having a total capacity many times greater than that of the transformer. Before this kind of trouble appeared, with the concentration of large amounts of power, it was desired and specified that the transformer regulation should be a minimum. To meet this specification a low reactance was necessary. Thus in many instances the impedance voltage was limited to from 2 to 4 per cent. If a transformer is assumed to have 3 per cent impedance voltage, and to be backed with sufficient generator capacity to maintain normal voltage, a current about 30 times normal will flow when a feeder leading from the transformer becomes short circuited. The flow of such a current in a medium or a large sized transformer produces electromagnetic stresses of many tons. The forces exerted are in such relation to one another as not only to flare the ends of coils over the supports for holding them together; but also to twist and distort the individual coils.

This sort of trouble has been cured by inserting separate reactance in circuit with transformers having low inherent reactance, by designing for higher inherent reactance, and by increasing the surfaces of coil supporting strips. Experience has shown that a quick-opening switch is not effective in protecting a transformer against the distorting forces of heavy current rushes in cases of short circuited lines.

CARE IN OPERATING

Where artificial cooling is used, the circulation of the cooling medium should not be neglected; the transformer cannot run continuously even under no load with the circulation shut off. The cooling coil of a water-cooled transformer is liable to become stopped up with weeds and grass, which restrict the flow of water, or a coating of dirt and mud may form inside the coils, decreasing the effectiveness of the cooling. Occasionally chemical action takes place between the water and the metal of the coil resulting in a formation that lessens the effective cross section. Systematic observation of the flow and temperature of the water and of the temperature of the oil in the transformer, will give an indication of approaching danger from any of these sources.

Another feature of cooling that sometimes leads to a critical condition is the forcing of the circulation on occasions of heavy overload. If a very large amount of cold water is forced through the coil, and the coil is in good condition as regards its internal surface, then the temperature of the oil is maintained at a value, under a very heavy overload, that gives no indication of the temperature of the transformer windings. It has been demonstrated in service that it is possible to seriously overheat the windings without unduly raising the temperature of the oil.

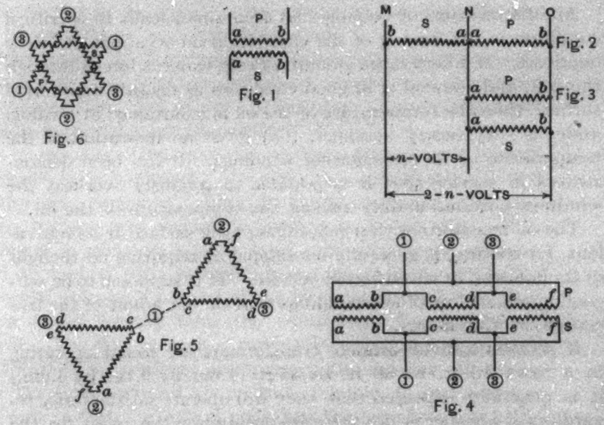
The oil transformer that relies upon tank surface or its equivalent, for cooling, is generally considered as requiring no thought in its housing, or attention in service. It is supposed to be self-cooling, regardless of surroundings that do not admit of the free escape of the heat.

If six 500 kilovolt-ampere transformers are found operating in a room 15 ft. by 30 ft. by 15 ft. (4.6m. by 9.1m. by 4.6m.) it is generally expected that they will operate satisfactorily regardless of whether or not there are openings in the room for the circulation of air. Now assuming the losses to be 2 per cent, there are 60 kw. of energy to be radiated. This is equivalent to 80 h.p. Imagine an 80-h.p. boiler making steam at its normal rate, for a room of the dimensions given above, on a hot summer day; this will give an idea of the necessity of proper ventilation of the room and of the spacing of the transformers. To limit the temperature rise of the air in the room to 5 deg. cent., would require the circulation of approximately 21,000 cu. ft. (594 cu. m.) of air per minute. The air in the room would have to be entirely renewed three times per minute.

It should not be assumed that the manufacturer is free of responsibility in questions affecting the operation of transformers. It is not only necessary to have reliability and efficiency, but the transformer case should be built so as to facilitate crude handling as well as crane handling; and connectors for changing ratio should be easy of access and manipulation.

CONNECTIONS

Frequent occasion arises for the determination of the effect of a certain combination of transformers. It is an easy matter for the operator to determine whether a combination is correct or not, by simply applying the voltage; but in case the test should prove it to be wrong, it is not always easy to figure out what the correct combination is.



SKETCH A

The following treatment of this question is based upon instances that have arisen in connection with systems in various parts of the country. Experience has shown that there are two main divisions of this question; combinations that show their effect immediately on being energized, and combinations that do not show their effect immediately on going into service, but develop objectionable and dangerous effects under peculiar conditions.

We will take up some instances illustrating the first mentioned division. Sketch B shows a combination that it was desired to use. The " line side " represents the high-tension or transmission side of the transformers, and the " load side " represents the low-tension or distributing side.

A three-phase problem of this kind embodies phase rotation and phase position. For simplicity, we will begin with a single-phase combination shown in Sketch C, similar to the three-phase combination shown in Sketch B. There is this difference between the three-phase and single-phase combination: the single-phase combination will always have the same phase rotation if the phase position is the same, while the three-phase com-

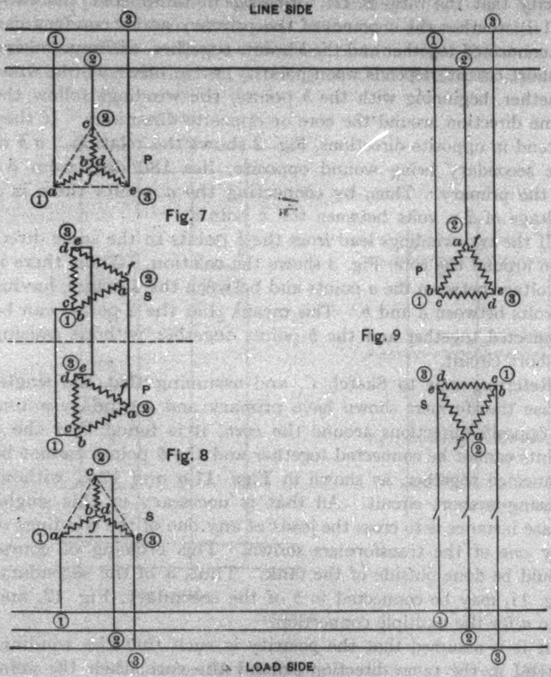


Fig. 7

Fig. 8

Fig. 9

Sketch B

bination may have the same phase rotation but a different phase position.

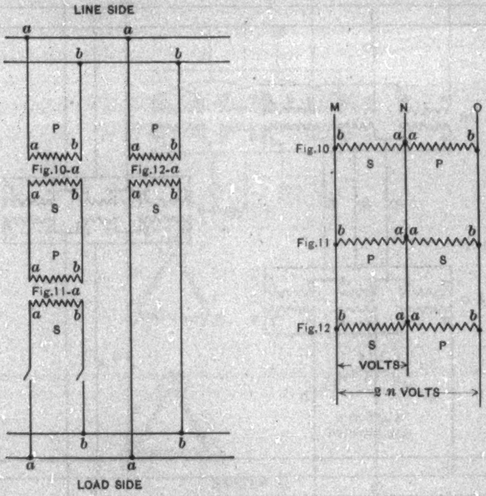
Referring to Sketch A, Fig. 1 represents a single-phase transformer with two primary leads and two secondary leads brought out of the transformer relatively as shown. Assume for simplicity that the ratio is 1:1. Having in mind that the ratio is 1:1, whether the *a* points of the primary and secondary can be connected together and the *b* points together, without causing a short circuit, depends upon polarity; or in other words, upon whether, beginning with the *b* points, the windings follow the same direction around the core or opposite directions. If they extend in opposite directions, Fig. 2 shows the relation. *a b* of the secondary being wound opposite, lies 180 deg. from *a b* of the primary. Thus, by connecting the *a* points there is a voltage of 2 *n* volts between the *b* points.

If the two windings lead from the *b* points in the same direction around the core, Fig. 3 shows the relation. Thus, there is 0 voltage between the *a* points and between the *b* points, having *n* volts between *a* and *b*. This means that the *a* points can be connected together and the *b* points together without causing a short circuit.

Referring now to Sketch *C*, and assuming that the single-phase transformers shown have primary and secondary wound in opposite directions around the core, it is found that the *a* points cannot be connected together and the *b* points cannot be connected together, as shown in Figs. 11-*a* and 12-*a*, without causing a short circuit. All that is necessary in this single-phase instance is to cross the leads of any one of the windings of any one of the transformers shown. This crossing of course would be done outside of the tank. Thus, *a* of the secondary, Fig. 11, may be connected to *b* of the secondary, Fig. 12, and *b* to *a* for the multiple connection.

If it is assumed that the polarity is such that the windings extend in the same direction around the core, then the combination of transformers as shown in Sketch C would be feasible. Furthermore, it would be feasible with any number of transformers in one of the multiple circuits as compared with the number in the other circuit.

The combination referred to in Sketch B contemplated the use of single-phase units with windings in opposite directions. It is seen in Figs. 4, 5 and 6 Sketch A that in a three-phase combination of transformers, the fact that the phase rotation is the same does not mean that the phase position is the same. Assuming a given three-phase line voltage impressed on the points 1, 2 and 3 of the primary, Fig. 4, there results the phase relation shown in Fig. 6 between the primary delta and the secondary delta. In other words, with transformers whose primary and secondary windings lead in opposite directions around the core, connected delta to delta, the primary delta makes a six-phase relation with the secondary delta. The method of arriving at this relation is shown in

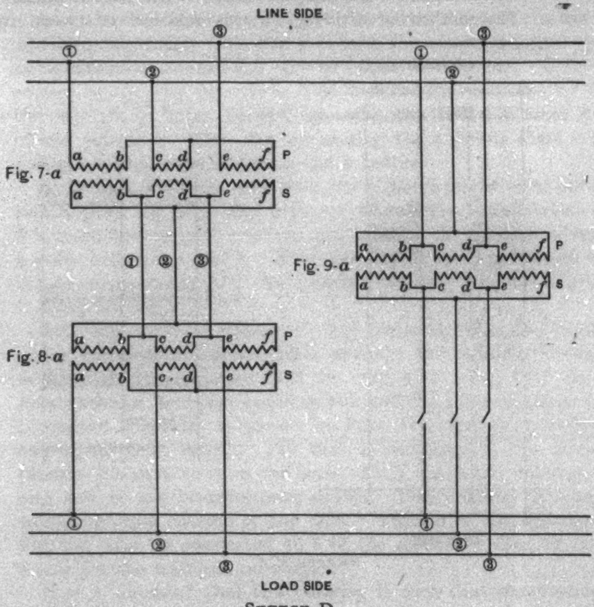


Sketch C

Fig. 5. Each secondary winding is shown revolved 180 deg. from its primary, and the points connected together in this figure for making both the primary and secondary deltas, are the same as the points shown connected together in Fig. 4. Fig. 6 is the same as Fig. 5 except that in Fig. 6 the secondary is shown superposed on the primary as it would actually be in practice. If we assume that the primary and secondary windings of the individual units are wound in the same direction around the core, then the points of the secondary

delta would coincide with the points of the primary delta and would not have the six-phase relation. Another feature noticeable in Fig. 5 and Fig. 6 is that the points 1, 2 and 3 of the primary and of the secondary, while not coinciding, show the same rotation.

We are now prepared to take up the main question as to whether the combination shown in Sketch B is feasible. Sketch D shows the individual transformer connections corresponding to the combination shown in Sketch B. The points 1, 2 and 3 of the primary represent the impressed voltage in Sketch B, and the transformer terminals upon which this voltage is shown to be impressed in Sketch D. Thus, of necessity, the primary points 1, 2 and 3 of Fig. 7 and Fig. 9 must coincide, since the corresponding numbers of the figures represent identical voltage



SKETCH D

points. The question is: what relation shall we find where the two multiple circuits come together on the load bus?

Keeping in mind that the primary and secondary are wound in opposite directions around the core we find in Fig. 7 that the combination of secondary windings, each shown revolved 180 deg. from its primary, gives a delta lying in such a position as to bring together the points shown connected in the secondary of Fig. 7-*a*. The delta in Fig. 7 cannot lie in any other position than the one shown, and at the same time bring together the points shown connected in Fig. 7-*a*. The relation between primary and secondary, therefore, is fixed. The primary of Figs. 8 and 8-*a* is the same as the secondary of Figs. 7 and 7-*a*, the delta of Fig. 8 lying in the same position as the delta of Fig. 7. The individual secondary windings of Fig. 8 are shown, each 180 deg. from its primary, to form a definite Y corresponding to the connections shown in Fig. 8-*a*. Figs. 9 and 9-*a* show a delta-delta combination of single-phase transformers of standard polarity. It has already been pointed out that the primary voltage figure represented by points 1, 2 and 3, Fig. 9, must coincide with the primary voltage figure represented by points

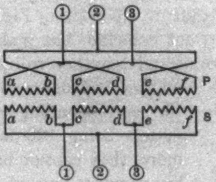


Fig. 9-*b*

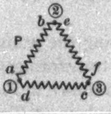
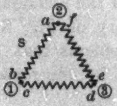
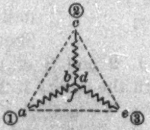


Fig. 9-*c*





S. OF Fig. 8 REPRODUCED

SKETCH E

1, 2 and 3 of Fig. 7. In the secondary of Fig. 9 each winding is shown arranged 180 deg. from its primary, making a delta with points connected together as shown in Fig. 9-*a*, such that, if superposed on the primary as it actually is in practice, would give a six-phase relation between the primary and secondary.

The secondary points 1, 2 and 3 of Fig. 8 and the corresponding points of Fig. 9 are seen to be fixed in their positions. According to the conventional practice of connecting the two circuits, as shown in Sketch D, in multiple, the points numbered 1 would be connected together, the points numbered 2 connected together and the points numbered 3 connected together. But if we refer to Sketch B we find that in superposing Fig. 8 upon Fig. 9, the points 1, 2 and 3 do not coincide, but make a six-phase combination, which if connected together will give a short circuit on the impedance of the combination, the corresponding points of the two figures being 180 deg. apart. Furthermore, they cannot be made to coincide by varying any of the connections to either the high-tension or low-tension line.

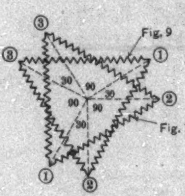
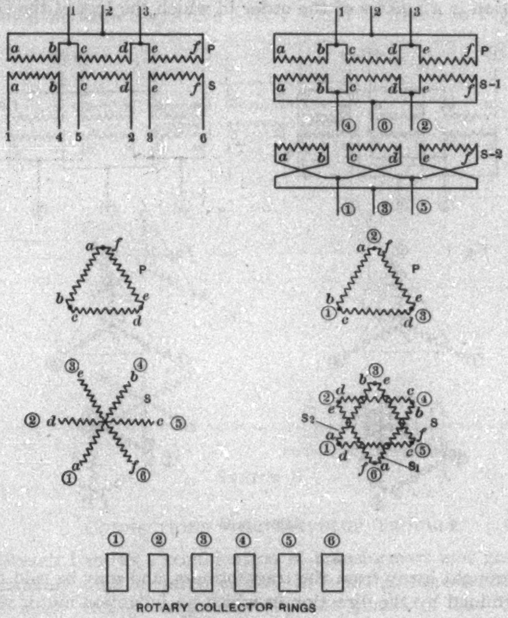


Fig. 13

By reversing the primary leads of the individual transformers of Fig. 9-*a*, Sketch D, as shown in Fig. 9-*b*, Sketch E, the points 1, 2 and 3 of the secondary of Fig. 9 are made to coincide with the points 1, 2 and 3 of the secondary of Fig. 8, as shown in Fig. 9-*c* and the secondary of Fig. 8 reproduced in Sketch E. A number of other problems that have arisen in practice may be explained in detail by the reasoning given for this instance.

It is generally understood that a Y-delta combination cannot be run in multiple with a delta-delta combination. Referring to Sketch B, the relations between two such combinations are shown in Figs. 7 and 9. Fig. 13 is used to show the secondary of Fig. 7 superposed on the secondary of Fig. 9. as it would actually be in practice. Referring to Sketch D, if the operator desires to make the trial of connecting the bank of Fig. 7-*a* in multiple with the bank of Fig. 9-*a*, he would connect the 1 leads together, the 2 leads together and the 3 leads together. But these corresponding points as shown in Fig. 13, are from 30 to 150 deg. apart. Furthermore, the phase rotation is reversed, so that to connect the corresponding points together would give a short circuit. It is commonly said that the secondary deltas in this instance are 30 deg. apart, but this statement is based upon the location of the points with the same phase rotation, and not upon the points that would ordinarily be connected in service.

Sketch F shows the usual combinations of three transformers for obtaining a six-phase voltage for synchronous converters.



SKETCH F

Fig. 1 of Sketch G shows a three-phase transformer that was desired to be operated in multiple with the one shown in Fig. 2. The connections were as shown, and it was known also that in the case of Fig. 1, the individual phases have their windings wound in the same direction around the core, while the individual phases of the transformer shown in Fig. 2, have their primary and secondary windings wound in opposite directions around the core. It is seen from the sketches that the deltas of the transformers coincide and that the phase rotation is the same for both transformers.

A study of the foregoing examples will show that, in order that two banks of transformers may operate in parallel, it is not only necessary to have the phase position of relative banks the same, but also to have the phase rotation the same. This phase rotation is a matter of the order in which the legs of the circuit are brought away from the transformers, and may be said to be determined by the direction in which an induction motor would run when it is connected to a circuit in a fixed manner. The phase rotation is not changed by changes in polarity nor in going from primary to secondary in a delta-delta or Y-Y combination, provided the legs of the circuit are brought away in the same order on both sides, according to conventional practice. In the case of a Delta-Y or Y-Delta combination, conventional practice, in connecting to the circuit, reverses the phase rotation in going from primary to secondary. This is illustrated in Sketch

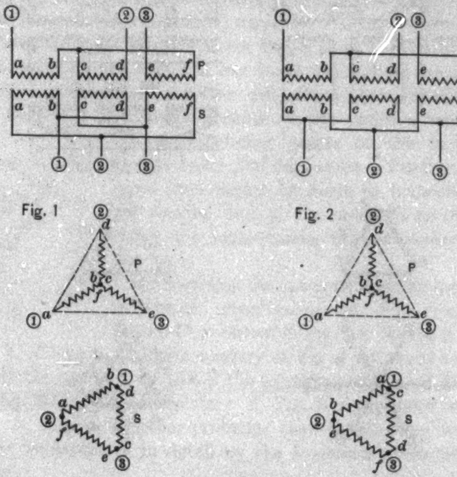


Fig. 1

Fig. 2

SKETCH G

B, Fig. 7, where the voltage points 1, 2 and 3 are in reversed direction around the triangle of the secondary from that found on the primary side, or on the secondary side of Fig. 9. Reversed rotation accounts for the varying degrees of voltage difference obtained between the 1 points, 2 points and 3 points of Fig. 13. If, in Fig. 7 Sketch B, 1 and 2 legs of the secondary circuit were interchanged, the discrepancy in phase rotation would be corrected and a uniform angular difference (30 deg.), of phase position between respective points would be found in Fig. 13.

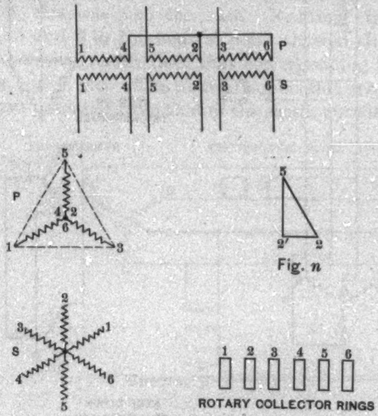


Fig. *n*

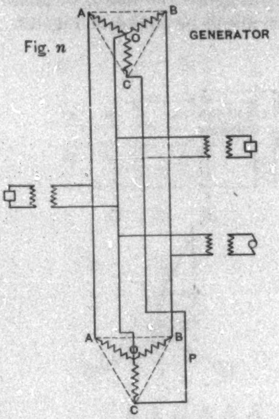
SKETCH H

Connections that Develop Trouble

Sketch I shows a combination of transformers and generator commonly used in large cities. In some instances the triple frequency voltage established by the generator has been of sufficient value to cause heavy triple-frequency current to circulate in the delta of transformers for three-phase service. It is understood that the triple-frequency voltage does not appear between lines but only between lines and the neutral point. (See paper by J. J. Frank, Proceedings A. I. E. E., March, 1910). Therefore, the fourth wire connected to the neutral point for the distributing system, admits the circulation of the objectionable current in the windings of the transformers connected as shown in Fig. *m*, Sketch I. This no-load current has been known to reach values ranging from 50 per cent to 90 per cent of the full-load current.

This objectionable current has been easily eliminated by simply disconnecting the fourth wire from banks of transformers used for three-phase service. If it is desired to ground the neutral of the distributing system the generator neutral may be grounded.

Fig. *n*



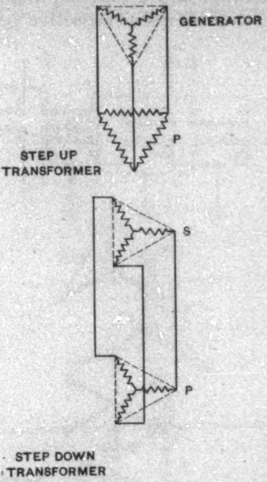
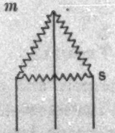
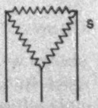


Fig. *m*



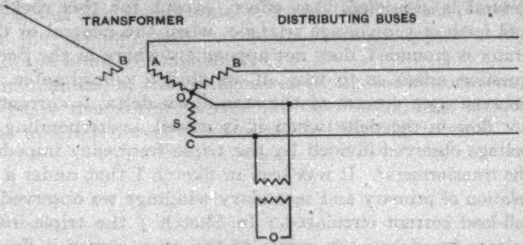
SKETCH I



SKETCH J

This keeps down the static electricity usually noticed in stations where the neutral is not grounded. It is not necessary to ground the neutral of the bank of transformers for the motors.

Sketch H shows the combination of transformers for six-phase split-pole converter service. There are two sources of triple-frequency current encountered in practice. In Sketch I it was shown that the triple-frequency effect originated in the generator. In Sketch H we have an instance of the appearance of triple frequency effect that results from the nature of the transformer. That is, any transformer may be so connected with other transformers as to show the triple-frequency effect inherent in all transformers. There was occasion to measure the secondary voltages with normal voltage impressed on the primary of the transformers shown, before the switch between the transformer and converter was closed. Each of the secondary voltages was found to be about 10 per cent higher than it was rated. Thus, it appeared that the transformer ratio was incorrect, but this was not the case. Readings taken from the points 1, 5 and 3 to the neutral point showed that each of the leg voltages was greater than that corresponding to the line voltage from 1 to 5, etc. The neutral connection was found to have a different potential from that of the earth, notwithstanding that the leg voltages were equal. The voltage diagram of a leg is shown in Fig. *n*, Sketch H. 5-2 is the measured voltage and 5-2′ is the leg value corresponding to the line voltage; so that 2′-2 at right angles to 5-2′ is the value of the triple-frequency component. This value holds true for each of the legs, and is best understood by considering the leg values in a plant at right-angles to a line passing through the true neutral point, the observed neutral being a point in the line out of the plane of the legs. Thus, if the measured leg voltage is found to be 10 per cent greater than the value corresponding to the line voltage, then the triple-frequency would have an actual value of about 46 per cent, assuming the true leg value to be 100 per cent and the observed value 110 per cent. This means that if the secondary windings are connected in delta and one corner of the delta is opened the voltage found at the open corner is



SKETCH K

about 40 per cent greater than the rated voltage. The ratio of transformation was found to be correct, comparing the secondary voltage with the primary leg voltage which is the voltage of the primary windings of any one of the transformers making the three-phase combination. Upon closing the switch between the secondary and converter a small magnetizing current circulated in the converter winding and caused the transformer voltages to drop to their normal value, which means that the leg values of the primary corresponded with the line values in the usual relation.

Sketch J shows a combination used for long distance transmission of power. Any triple-frequency component in the generator voltage simply results in shifting the neutral of the generator in case the neutral is not grounded and in rocking the three-phase voltage impressed on the transformer in case the neutral is grounded. Its effect, except for this rocking back and forth of the voltage triangle, when the neutral of the generator is grounded, does not appear anywhere in the line. The question arises as to why, if we find a considerable voltage between open corners of the step-down delta, a current would not flow in the delta when it is closed, corresponding to the voltage observed divided by the triple frequency impedance of the transformers? It was seen in Sketch I that under a similar relation of primary and secondary windings we observed nearly full-load current circulated. In Sketch J the triple-frequency voltage found between points of the open corner is due to the nature of the transformer, and therefore, only a very small magnetizing current is necessary to re-adjust the voltages. The current is inappreciable whether the neutral points are connected together or not.

Sketch K shows a combination of three single-phase station transformers for distributing purposes. The connection is $Y-Y$, and while not a common one, is used in at least two large cities in the United States, with this difference, that in one, both the high tension and low tension neutrals are grounded, while in the other only the low tension neutral is used for a fourth wire service. In the instance where the high tension neutral was not used, considerable trouble was experienced in the unbalancing of the phase voltages of the distributing system. If the load is perfectly balanced and the transformers used in the station have identically the same magnetizing current, then there would be no unbalancing of distributing voltage. However, experience has shown that it is practically impossible to obtain such perfect conditions and therefore this combination is bound to result in extreme unbalancing of voltages.

In order to understand why this combination is so easily unbalanced it will be assumed that current is being drawn between the fourth wire 0 and the point *C*, Sketch K. This current represents unbalancing and is drawn from the winding *O C* of the secondary of a single-phase transformer in a three-phase combination. But there cannot be current in the secondary without corresponding current in the primary. Thus, in addition to passing through *O C* in the primary, the current must also pass through either *O A* or *O B* or both. No current is passing through *O A* or *O B* of the secondary. Therefore, any current passing through *O A* or *O B* of the primary must be magnetizing current. Thus, with very small current delivered between *O* and *C* of the secondary, the voltage between *O* and *C* of both the primary and secondary becomes approximately zero and the point *O* extends to *C*.

The unbalancing of the voltages was eliminated by connecting a three-phase transformer across the distributing lines in such a way as to admit the circulation of the balancing current.

DISCUSSION ON "THE REGULATION OF DISTRIBUTING TRANSFORMERS", "TEMPERATURE GRADIENT IN OIL IMMERSED TRANSFORMERS", "DISSIPATION OF HEAT FROM SELF-COOLED, OIL FILLED TRANSFORMER TANKS", "PROBLEMS IN THE OPERATION OF TRANSFORMERS", PITTSFIELD FEBRUARY 15, 1911.

W. S. Moody: I will not attempt to contribute to any of the discussion, but I wish to point out one idea that has been specially in my mind in connection with the papers that have been presented this afternoon. Most apparatus, whether electrical or otherwise, requires some arbitrary or empirical formula to be used in its design. Transformers, among electrical apparatus, are, I believe, as little subject to these " cut and try " methods as any other class of apparatus, except for two characteristics that have been brought to the front in the discussion this afternoon—*viz.*, the calculation of the dynamic forces that must be resisted, and the predetermination of temperature rise.

For the first, we now have in the formulae recently developed the means of knowing what these forces are, and with this knowledge, taking care of them is a relatively simple matter.

When sufficient mechanical support has not been furnished for transformer windings, it has been due to an under-estimate of what these forces are likely to be, rather than any special difficulty in providing proper supports when the actual force to be encountered is known.

With reference to the second point—*viz.*, temperature rise, there has been a great lack of definite data. We can calculate a new transformer in nearly every other characteristic with great accuracy, but if the design is radically new, one could not, in the past, tell what the real capacity would be with a given temperature limit until tests were made.

Having determined the temperature by test, it is usually necessary to re-proportion the parts once or more to obtain the desired characteristics on the re-rated design.

To predetermine temperature rise one must consider a vast number of details, such as are considered in Mr. Weed's paper, and which have previously been neglected or allowed for in a very arbitrary way.

With such formulae as are discussed in Mr. Harper's paper, and such data and formulae as are considered in Mr. Weed's paper, I feel that there is no further excuse for the use of any " cut and try " methods being pursued in transformer design.

Henry Pikler: The papers we have just heard as some of the papers we heard earlier, interest probably the designing engineer more than the operator, since after all the operating engineer is satisfied if the apparatus in service fulfills the requirements of guarantees attached to it.

As to the various papers, Mr. Allen's paper on the " Regulation of Distributing Transformers " is a very able and clear presentation of the relation between resistance and reactance in the regulation of the transformer. A great many examples have been worked out and various formulas given to calculate the regulation, but in general I dare say I do not find the broad point of view from which the influence of both the reactance and the resistance could be clearly pictured. The following may be a clearer and simpler presentation of the facts: The regulation depends upon the mutual relation between resistance and reactance in the transformers; at loads of unity power factor the regulation is approximately equal to the resistance drop, and at loads of zero per cent power factor, it is approximately equal to the reactance drop; at power factors between the two, the regulation will be found between these two figures that is the resistance drop and the reactance drop combined.

Towards the end of the paper a method is given whereby good regulation may be obtained in transformers intended to be used for three wire distribution, lighting transformers. At this point it may be said with probably greater simplicity: In small size lighting transformers the resistance is the predominant component of the impedance. In larger transformers the reactances is of larger amount. Therefore, when we want to connect various parts of the transformer windings into parallel, so as to obtain proper three wire distribution and at the same time best regulation, in small transformers equal resistances in large transformers equal reactances should be connected in parallel.

I consider one of the most interesting papers, presented to us, that by Mr. Green on " Problems in the Operation of Transformers ". Anybody who has had a chance to install transformers, to observe them in operation and to note the various phenomena in connection with them will appreciate the complexity of these phenomena and the difficulty of their clear presentation.

One of the most frequent sources of troubles in connection with transformers is their installation. At this point I wish to call attention to the fact that while almost always the transformer is tested at the factory of the manufacturer, in the presence of a representative of the customer, afterwards the transformer is installed frequently by the customer himself. The transformer is often found satisfactory in every respect at the factory, yet, at its installation breakdowns are not infrequent. Causes of this may be various and I shall refer to them later on, but I desire to use this occasion for suggesting the adoption of some rules, if that is at all possible, whereby the customer be held responsible for injuries to the transformer when he does the installation after having tested and accepted the transformer at the factory. The manufacturer should be held responsible only when his representative does the installation.

The causes of the breakdowns in transformers may be divided into two great classes. (1) Internal causes in the transformer itself. (2) External causes.

1. As to the internal causes I believe that defects in design, electrical construction, insulation, will show up at the factory if the apparatus be tested rigidly. At the same time there may be defects in the manufacturing which develop a weakness in the transformers only after it has been installed and operated for some time. At the present time the use of solid compounds for impregnation of the windings is almost universally adopted. The solid compound marks a great improvement in the modern transformer because it makes those mechanically weak coils of which we heard so much this afternoon, stronger by cementing together the turns and the insulation between turns and layers in the winding. At the same time the application of this solid compound is not so easy as it may look at first glance. If not done properly there may be found bare spots in the winding which have not been reached by the compound. At such places the mechanical wear and the dielectric stresses combined may create injurious effects in the course of time.

Also improper drying out before installation may be the cause of a breakdown.

One very good point brought out in this paper which I believe hits the nail on the head as regards internal causes, is the suggestion that the electrostatic capacity of the parts of the transformer should be small.

It is very interesting to follow the history of the design of transformers and of the means suggested for their protection. Years ago we heard that the weakest element in a transformer were the first turns and they ought to be protected most carefully by insulating them more than other parts, it was earnestly recommended to put a choke coil in series with the transformer or use the choke coil internally or even to develop the first few turns as a choke coil. *Now* we hear that it isn't so much between the first turns where the breakdowns occur but between other turns or parts of one winding. It would be very interesting to take oscillograms for the purpose of obtaining the voltage distribution between the various parts of the transformer winding under various conditions as switching surges, etc.

Again in this paper we find reference to forces in transformers arising on short circuits; it is suggested that the transformer be designed with sufficiently high reactance in order to reduce the short circuit currents, and the resulting forces. At this occasion I wish to say that contrary to the statements made by previous speakers that the low regulation of the transformer is chiefly due to the customer's demands for such, my findings are different: Low regulation is a natural sequence in transformers of large sizes; with the generally adopted principles of design and the economic utilization of materials, we cannot help but obtain a decreasing reactance with increasing output. Furthermore, we mustn't forget that it is not the per cent reactance that should be considered in this problem but it is the numerical value in ohms. To make a large transformer of high reactance is not so simple as it may seem at first glance. A high reactance transformer means an expensive transformer. It means a transformer with many more ampere turns than in a low reactance transformer. More ampere turns means more copper and copper is an expensive material; besides copper requires winding space, hence a bigger iron core, in other words a larger and a more expensive transformer. On the other hand, if the high reactance be created by increasing the space between primary and secondary windings, we again get a larger winding space and larger core; in addition a tremendous self inductive field will be developed between these windings which is conducive to high eddy currents, heating and a reduced efficiency.

2. As to the external causes of breakdowns I wish to emphasize very strongly that in this respect the entire power system must be considered from the prime mover to the distributing apparatus. Concentrated condensers in parallel with the transformer created by neglect of grounding supports of high tension wiring, switching apparatus, etc., can pile up tremendous voltages on the system which may find an outlet into the transformer. Analogously concentrated choke coils may also be detrimental in the case of great variations in currents. Defective governors of prime movers, variations in speed and voltage, high winds which bring line wires on poorly constructed transmission systems in oscillation, improperly installed protective apparatus, surges of all kinds in connection with concentrated condensers as described above are the most frequent sources of breakdowns of transformers. Therefore before installing a transformer particularly on a high voltage long distance transmission system everything ought to be reviewed from the point of generation of the energy to the point of distribution.

As to the paper on " Dissipation of heat from self cooled oil filled transformer tanks ", again I do not find that broadness I looked for on this subject; although I must say that the paper presented by Messrs. Frank and Stevens is very valuable particularly for the many tests and numerical results given: In self-cooling transformers we find a great disadvantage results from the fact that the surface of the tank is not uniformly efficient. The useful surface is almost entirely the upper one; the lower portion depending of course on the proportions of the tank, is quite useless. Before we start to adopt various artificial means for increasing the radiating surface of the tank, we should first take advantage of the surface we already have, that is, make it as nearly uniform in efficiency as possible. There is one transformer tank that meets this requirement, this is the one with the external return pipe connections between top and bottom. This tank does not represent a novel idea; about eight years ago the Stanley Electric and Manufacturing Company—Mr. Chesney who is present will probably remember—had some transformer tanks in the shop of exactly that type, this type of tank was abandoned, however, on account of the excessive cost, and the difficulty at that time in making the welding between the coil and the tank.

In comparison with the European practice it ought to be pointed out that European transformer designers and makers are far ahead in making self-cooling transformers and tanks, and it is not unusual that capacities as high as 3,000 kw., or over are made for self-cooling purposes. One reason for this may be that the European standard for the rise of temperature is 20 to 25 degrees higher than the American standard. I personally think that our temperature limitations are too low, particularly in view of the great improvements made in insulating materials during recent years. I think it would be absolutely safe to allow a temperature rise even as high as 60 degrees instead of 40 degrees, even in the over-heated power station.

E. G. Reed: Mr. Pikler has just made the statement that the European practice in regard to self-cooling transformers is superior to that in this country, referring to the size of units which can be cooled in this manner. The above statement should not be permitted to go unchallenged, as we are to-day successfully building in this country, transformers of this type up to as high as 3000 kv-a. capacity. The method of cooling employed is to provide oil tubes external to the transformer case through which the hot oil flows, being cooled in passing. This is a distinct advance in the art of transformer design. Such self-cooled units find their use, for example, in isolated substations where water for cooling is very difficult to secure and where it is desirable to dispense with an attendant.

Just a word in regard to Mr. Allen's paper: It seems to me that the most important point in this paper is the suggestion of the standardization in the method of calculating regulation on the basis of not taking into account the exciting current. If this method is correct, and I think it is, as it lines up with the Institutes' definition of regulation it should be generally adopted.

Louis F. Blume: Before regulation was defined by the American Institute of Electrical Engineers, it was proper to include exciting current in its calculation for transformers, because then by regulation, was understood the total drop at full load in the transformer from primary applied to secondary terminal voltage. When the Institute defined regulation as the difference between no load and full load primary voltage the consideration of exciting current became negligible. Thus, as Mr. Allen points out, the only influence of exciting current upon regulation lies in the fact that at no load it is greater than at full load. This difference, however, being so very small, is only of theoretical interest.

E. A. Wagner: The paper by Mr. Allen is typical in showing that the transformer engineer does do things accurately. Our worthy President intimated that transformer engineers did not get very close in their calculations, but rather guessed at them. Mr. Allen shows several formulae for the calculation of regulation, and in these several formulae he works out to hundredths of one per cent. I think it is a matter of choice, no matter which formula you take, and I know that there is considerable discussion at times as to the method of calculating the regulation and working it down to very fine quantities, and I believe it is within the province of the Institute to make a recommendation as to some definite formula, so that in the case of a discussion between a consulting engineer and a manufacturer as to the method of calculating the regulation, there is something to refer back to.

It may be true that the formulae would be subject to such discrepancies as stray exciting current or magnetizing current might produce—you might want to segregate them—but I do not think that has any direct bearing on the matter, and I want to make a recommendation that this matter of having some recommended formulae for calculating regulation be taken up by the Standardization Committee.

In regard to Dr. Steinmetz's paper, which I did not discuss previously, would state that I had occasion a number of years ago to see an actual demonstration of the forces or stresses which followed from a short circuit. It happened at Niagara Falls, and was a case of 200 kw. transformer subjected to short circuit, and it showed that the busbar winding, which was about one-half in. by two in. was strained and actually forced and distorted out of place, and at the same time, due to the same causes, the cables in the alley running from the power house were thrown off the rack—that was an actual demonstration and showed at that time that these stresses did take place.

In regard to the paper by Messrs. Frank and Stephens, on the dissipation of heat from self-cooled oil-filled transformer tanks, my experience is in accordance with theirs. I think you will obtain about 50 per cent, make the figure a constant of 50 per cent, less watts per square inch, with a corrugated sheet steel tank than with a plain cast iron tank, and I have tried to follow that out carefully, and find that the practice agrees very closely with their curves. I think that the tendency to run to very deep narrow slots will give us dead air pockets, and believe the best results will be obtained by slots or corrugations having ratios of a depth not more than twice the opening. I have not made any attempt to calculate this and arrive at a mathematical conclusion, but as a matter of practice find that the above general rule gives the best results. I do not think that good results will be obtained from the boiler tube tank, because I have tried schemes of pumping hot oil into the bottom of the tank, and *vice versa*, taking cold oil from the bottom, and circulating it from the top, so that the surface of the tank reaches the same temperature throughout—under these conditions, the lowering of temperature with a transformer having a 40 degree rise without the circulation, my tests showed we gained one or two degrees lower rise which is not enough to warrant the additional complications which this system involves.

C. A. Adams: Referring to sketch H of Mr. Green's paper, it may be of interest to show why there must be a 3rd harmonic in the transformer flux and induced e.m.f., with three-wire star connected primaries, and secondaries on open circuit.

It has often been shown that a sinusoidal flux in a closed iron magnetic circuit such as that of the ordinary transformer, requires a magnetizing current with a considerable 3rd and a lesser fifth harmonic. But a third harmonic current cannot flow in a three-wire, three-phase, star connected system, since the third harmonics in the three wires are in phase when counted positive in the same direction along the line, and would therefore be all flowing towards the star neutral at the same instant, which is obviously impossible without a neutral return wire.

Assume the secondaries on open circuit, and neglect the fifth and any higher harmonics. The currents in the three transformer primaries will then be sinusoidal. Neglecting eddy currents, the relation between the m.m.f. and the flux is given by the hysteresis loop of Fig. 1. The sinusoidal magnetizing current or m.m.f. is plotted against time in Fig. 1. In both curves, time is indicated by the arrow-heads. The flux-time curve, derived in an obvious manner from the hysteresis loop and the m.m.f. time curve, is curve *B* of Fig. 1. The fundamental of the flux curve is shown in curve *B*, and the residual or higher harmonics in curve $B_{3,\,5,\,\text{etc}}$. From this it is clear that there is very prominent third harmonic in the flux curve, which increases with the maximum density.

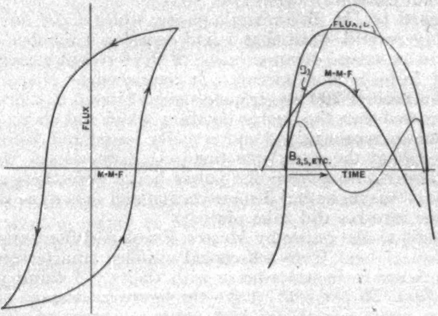


FIG. 1

Thus on open secondary circuit, there is a pronounced third harmonic in the flux and therefore in the primary and secondary e.m.fs. It is obvious that these third harmonic e.m.fs. in the primary phase or star e.m.fs., do not affect the line e.m.f., the wave-shape of which is determined by the supply alternator. (The two third harmonic e.m.fs. connected in series between any two primary lines are 60 degrees apart in fundamental degrees, when counted positive from line to line through the star neutral, and therefore 180 degrees apart in third harmonic degrees. They thus neutralize each other and do not appear in the line e.m.f., but merely cause a rotation of the star neutral point).

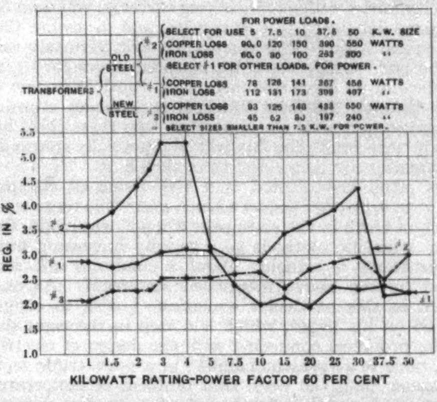
If now the secondaries be closed, either in simple delta or diametrally to a six-phase converter as indicated in Mr. Green's sketch H, the third harmonic, unless exactly neutralized by some third harmonic dynamic e.m.fs. in the converter, will produce third harmonic currents in the secondaries, the m.m.f. of which will tend to oppose their cause, namely the third harmonic fluxes in the transformer cores, *i.e.*, these third harmonic currents in the secondaries will act as exciting currents, will tend to supply the primary deficiency in this respect, and to restore the flux to the sinusoidal form. This restoration will obviously take place up to the point where the third harmonic secondary e.m.fs. are just sufficient to drive the necessary third harmonic exciting currents through the local (internal or leakage) impedances of the secondaries, and of the converter. As these third harmonic e.m.fs. are very small, the flux will be practically sinusoidal when the secondaries are connected as in sketch H.

It has often been stated that the design of electrical machinery is an *art* rather than a *science*, and while there was doubtless much of truth in the statement when it was made, the application of scientific methods to a rapidly increasing number of design problems is bringing about a condition not accurately described by the above mentioned statement. As one much interested in this particular evolution, I wish to congratulate Mr. Weed on his paper, which is a step in the right direction. Of all the problems connected with the design of electrical machinery, none is at present handled in a more crude and superficial manner than the very vital problem of temperature rise. To be sure, from the standpoint of scientific accuracy, the problem is hopelessly complex, but there is much room for improvement before we begin to approach that ideal, and every step means more rational and more economical designs.

A. E. Walden (by letter): Mr. C. E. Allen's paper on "The Regulation of Distributing Transformers" is very interesting, and is in line with the method the writer has been employing for over eight years for selecting transformers for power service. The small transformers were tested with actual load, both with lamps and choke coils, obtaining actual drop directly. The manufacturers' claimed regulation is shown in the chart for three types of transformers, two using the old iron or steel, and one the new steel, and the method of selecting to get the best regulation. Actual tests taken have given better regulation than claimed by most manufacturers.

Mr. Allen's paper does not bring out very clearly the resultant loss in feeders due to poor regulation, with consequent voltage and power increase at the generating station, and the increased power required at exciter, due to lower power factor in the motors or transforming devices. In the operation of generating station and the distribution system of to-day, considering the size, the condition of low power factor deserves more attention that it has heretofore been given.

In a large distribution system at low power factor, such as is usually found with induction motors, the feeder loss with an increased drop of three or four per cent in transformers will be found to be considerable in the aggregate. In a generating station of 8,000 h.p., which the writer inspected recently, the power factor was below 70 per cent during the day, due to the fact that the load was nearly all motors. This will increase this loss considerably over iron loss.



It should be noted, further, however, that the regulation of transformers tends to improve slightly with power factors below 60 per cent.

Will Mr. Allen kindly explain what the increases in cross-section of the cores would be, also increase in weight per cent, to improve the regulation to that shown by curve No. 1. Also approximately what would be the increase in transformer cost if this was done, or could be done without changing the number of turns of the copper?

Ralph D. Mershon: I am sorry I have not had an opportunity to study these papers. I am especially interested in the paper by Mr. Weed and in that by Messrs. Frank and Stephens, not only in their bearing upon transformer design but also in connection with other engineering work where almost exactly similar problems arise relative to cooling. There does not seem to be much published data applying to this problem, and in some cases where I have required data I have been helped out by information furnished by some of my friends engaged in transformer design. But the information they could furnish was not nearly as comprehensive as would be generally desirable.

Figs. 5 and 7 of the paper by Messrs. Frank and Stephens show corrugations of such form that the section of the air space within the corrugation is greater than the corresponding oil space. I should like to ask the authors whether they have arrived at a method of determining the relation between these sections for the best result and if so what that method is.

There is another feature of the problem somewhat similar to that of the relation between the sections of the air and oil spaces in the corrugations. That is the best relation between the areas of tank surface exposed to air and oil respectively. Suppose we have a cast iron tank, for instance, having ribs on the inside and ribs on the outside. We may make the ribs on the inside and outside of different depths so that, within limits, we may vary the relation between the area of the tank in contact with the oil and the area in contact with the air. Now it would seem to me that the temperature drop to transfer a given amount of heat from the oil to a given area of tank surface would be less than that required to transfer the same amount of heat from the same area of tank surface to the air and that, therefore, less area would be required on the oil side than on the air side. It would be interesting if the authors could give us data bearing upon this point.

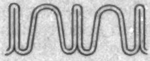


FIG. 1

It is not necessary to have a cast iron tank in order to control the ratio between the inside and outside areas. It can be done in a corrugated tank by collapsing some of the corrugations as in Fig. 1 and at the same time the relative sections of the spaces included in the corrugations can be controlled as indicated in the paper.

C. W. Stone: I have one or two questions in mind that I would like to ask—one is in relation to Mr. Allen' spaper. Fig. 9 shows a transformer which he calls a distributed shell type transformer, and Fig. 12 shows a core type of transformer. I do not see the difference. I wonder how he got at the name distributed shell type transformer. Apparently they are both core type. I think Mr. Allen could have brought out more prominently the increased cost of the transformer, and that bears out the point Dr. Steinmetz referred to, that the customer forces the price of the transformer down. If he has not done it, the manufacturers competing for the business have done it, which amounts to the same thing.

Mr. Pikler spoke of the breaking down of the transformer occurring inside the transformer, in other places than the end turns, and he suggested this matter should be investigated. It has been investigated by the oscillograph with interesting results which will be brought out later in another paper.

I notice a point in Mr. Green's paper which I think is particularly interesting to all designing engineers as well as operating engineers, in referring to the percentage of puncture between high-tension and low-tension windings, or between the windings and laminations, as being negligible, as compared with the percentage of punctures between turns. That is based on years of experience after many investigations of burn-outs of transformers I do not think it is often given consideration.

Another point that Mr. Green makes is one that operating engineers overlook—they seem to think, if they put a lightning arrester on the line, they are free from trouble, and that if the transformer breaks down it is due to a defect in the transformer. I want to point out that the best type of lightning arrester that can be conceived will not protect the transformer, particularly if they are switched on the high-tension side. There will be internal surges which will break the transformers down, regardless of the lightning arrester. Put on all the lightning arresters you can get and then put on some more, and it will protect you from surges outside, but will not save the transformers. You must provide proper switch transformers, and particularly avoid switch transformers on the high-tension side or else you will have a breakdown.

Another point which Mr. Green makes is the question of external reactance. I am a great believer in external reactance. I am also a believer in internal reactance. I think it is a good thing to have, the more the better. I think as the systems grow larger and larger there is less need for what is called good regulation. The diversity factor which is coming into our central station work to-day means that our transformers are loaded a greater proportion of the time—consequently there is less need for the best regulation; on the other hand, as our diversity factor does come into the operation of our systems, our systems become larger and there is a greater need for reactance. Reactance in the transformer itself does a certain amount of good; reactance external to the transformer does still more good. I think that is also true in regard to generators. And I think it is a subject which should be considered in all large stations and provision should be made for the installation of external resistance, if not at the time of the installation of the transformers, at some later time.

I think there is something in Mr. Wilson's suggestion, and I would suggest that the Standards Committee take up the point, and that is the question of the temperature rise of transformers, particularly water-cooled transformers—should they be based on the air test, or should they be based on the water test. I think these two factors are important and should be considered, and they are not now considered in the Institute rules.

E. F. Alexanderson: In the design of any electric machine which is cooled by an effective system of forced ventilation the greatest problem is to predetermine the temperature gradient between the conductors and the ventilated surfaces. After the heat has been carried to a metal surface it can easily be carried off by the air. As an illustration, I wish to mention a convenient method to determine the heat radiation in machines cooled by air holes running crosswise through the laminations of the core. As result of test of various machines the watts per square inch radiated on the duct can be expressed:

$$\text{Watts per square inch} = 1 + \frac{\text{velocity of air}}{1000}$$

The velocity is expressed in ft. per min. based on 75 degrees rise of the conductors and a temperature rise of 35 degrees to 40 degrees including incoming and outgoing air. The formula is, of course, only a thumb rule, but I wish to point out the magnitude of the quantity. If the velocity of the air is 2000 ft. per min. the radiation is 3 watts per square inch or 10 to 20 times as great as the figures mentioned for exposed coils in transformer design. This indicates that the largest temperature drop is in the insulation.

There is another circumstance that points to some peculiarities of the heat conductivity of insulation. The behavior of some transformers indicate that the temperature rise of a ventilated coil increases faster than the watts per sq. in. In other words, the heat conductivity changes considerably with the temperature. In view of this the question would seem pertinent, what is the heat conductivity of the various insulating materials, and I believe it would be of benefit for machine design in general if rules for determining the heat conductivity of insulation materials received as much attention by the Institute as similar data for dielectric strength.

Henry A. Pikler: I want to refer, in a few words, to the remarks made by Mr. Stone—he pointed out two things, one is the switching of the transformers on the high tension line; he desires to have some method devised and adopted whereby this could be avoided; in other words, he wants to see some rules introduced and accepted by the customer or the operator that transformers should not be thrown directly in the high tension line; the other thing that he pointed out, is that the introduction of reactance outside or inside is desirable. It is very interesting to note how intimate the relations between these things are. As to the first point, I do not think that is feasible. I cannot imagine any way whereby we could avoid throwing the transformer on the high tension line directly, except by shutting down the power entirely, if this transformer be the first transformer at that point. If we insert reactances in the circuit—let us say, more generally speaking, a series impedance, the result will be the distortion of the sine wave generated by the generator, at the terminals of the transformer.* This, of course, is quite serious, because we want to avoid the higher harmonics. With the introduction of the reactance, particularly at the moment of throwing on a transformer on the line, we will introduce these higher harmonics in a greater measure, than if we do not use the series reactance outside of the transformer circuit. And if the series reactance does not cause this then this proves its ineffectiveness for the purpose it was intended for.

C. P. Steinmetz: Regarding the remark made by Mr. Stone on the undesirability of high tension switching, I desire to endorse it, and still more particularly to draw attention to one interesting feature. We very often have done, and still occasionally do, things which we should not do, but we do them because we do not know any better, and as result, apparatus occasionally broken down by some mysterious phenomenon, which would not have been mysterious but for lack of knowledge. One of these things is the high tension switching. It has to be done, and will be done, but the less we do it the better it will be. We never realized this until we had the oscillograph on the high tension switch on very high voltage, long distance lines. It is easy to specify and say you must do it—certainly some time you may do it—but after looking at the oscillogram you will realize that the more we avoid high tension switching, the better it will be for the apparatus. In Fig. 1 is shown the oscillogram of a cumulative oscillation, resulting from high tension switching. Not shown in this oscillogram is the momentary and extremely local very high frequency traveling wave starting the oscillation, which is estimated of a frequency of two million cycles, and measured by its disruptive effects.

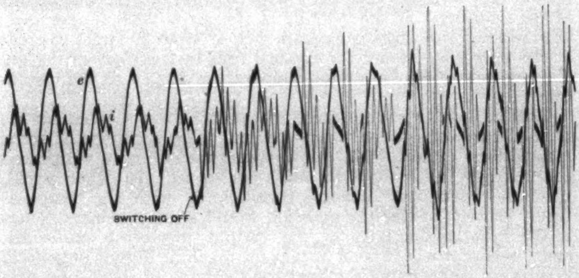


FIG. 1

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*H. A. Pikler, effect of series resistance in the primary circuit of a transformer. *Electrical World and Engineer*, 1903, p. 218.

Now, in regard to reactance, the place for high reactance is not in the high voltage line, where the high tension switch is objectionable. When you have a line in which you have to go to 100,000 volts, you are fairly certain there will be a voltage drop of ten per cent or more, whether the transformer has a high or low reactance, because the power which can flow through the transformer is limited. It is in those systems where the power is unlimited and the drop is negligible, a different class of systems, where the destructive effects of low reactance have been conspicuous.

When you speak of reactance, however, one thing must not be overlooked. If you say, a four or six per cent reactance is desirable for safety, that means you must have the reactance when you need it. It is wrong to put in an iron-clad reactive coil, which gives four per cent reactance at full load current, and when you get 25 times full load current, the reactance disappears by magnetic saturation, and wave shape distortion comes in. This has not been mentioned, because it is obvious. If you put reactance in to limit the short circuit current, the reactance must be there under short circuit, and this excludes the use of iron. In a transformer the maximum flux on short circuit is only full voltage flux, and magnetic saturation at short circuit thus cannot occur in a transformer, but in an additional reactance, it may, if iron is used, and that mistake has been made more than once, to use iron in power limiting reactances, with the obvious result, that the reactance was not there when you wanted it, and so did not serve the purpose for which it was designed.

J. M. Weed: Mr. Alexanderson's equation for cooling with forced circulation of air is represented by a straight line curve between watts and air velocity, cutting the axis for watts at one watt per sq. in. This line, no doubt, approximates the actual physical conditions for the high air velocities occurring in machines. For low velocities such as we find in the air which cools the self-cooled transformer the actual curve will be found to droop from the straight line and to cut the axis not far from the zero point. A similar condition exists with reference to the action of the oil in cooling transformer coils. This does not indicate that the largest temperature drop is in the insulation, as was suggested by Mr. Alexanderson, but rather that a very large temperature drop exists from the surface of the coil to the oil or from the surface of the tank to the air with the slow velocities occurring with natural circulation. This temperature drop at the surface is very much reduced by means of increased velocities obtained by artificial circulation. Some consideration was given to this matter in my paper and some also to the question of heat conductivity of insulating materials.

I would say that there must be something wrong with the transformer tests which showed a temperature rise increasing more rapidly than the watts per sq. in. producing this rise, since I have found from a large number of tests that there is a distinct tendency in the other direction. I have not found any definite variation in the thermal resistance of solid insulating materials, but do find a reduction of the equivalent thermal resistance at the surface of the coil, or the tank, as the watts increase, which I have attributed to the increased velocity which is automatically produced in the cooling fluid.

Mr. Mershon's questions about corrugations, and relative areas of surfaces exposed to oil and air, are partially answered in the last few paragraphs of my paper. To be more explicit, without being too exact, I would say that the space on the air side of the corrugations may, to advantage, be made from two or three times as great as that on the oil side. The width of the oil space may be reduced to from one inch to one-half inch, depending upon the height of the tank, without causing a serious drop in the oil temperature while passing downward from the top to the bottom of the tank. The width of the air space should vary from one to two and one-half inches, depending upon the height of the tank and the depth of the corrugations. If this space is too large the heat does not sufficiently penetrate the enclosed air, and part of the space is wasted, while if it is too small the friction to the passage of the air is too great, and its acceleration is not sufficient to draw in enough new air to keep its temperature down to a point which is properly effective in absorbing heat from the surface of the tank.

Within limits the higher the tank the wider the corrugations should be, both inside and outside, and the deeper the corrugations the wider they should be.

It is instructive, when considering the size of the corrugations, to reflect that with a given ratio of pitch to depth of corrugation, and given perimeter, the area of the tank surface will be the same whatever the size of the corrugation. The volumes of air and oil brought within the corrugations, and thus brought within effective range of the surface, will depend however upon the size of the corrugations. If the reduction in size is carried to the limit, the conditions of cooling approach those of a plain surface, which gives the minimum cooling for the given perimeter, although we have not reduced the area of our corrugated surface. Thus, within limits, the larger the corrugations, the more effective the surface.

As to the relative amounts of surface which should be exposed to air and oil respectively, if there were just so much total surface which could be distributed at will between the oil and the air this question would be more logical. With the cast iron tank with ribs we can make either surface what we wish, regardless of the other. Though the ribs may be said to be less important on the side toward the oil than on the side toward the air, since the temperature drop from the tank to air is normally greater than that from the oil to the tank, yet they are valuable on both sides. Because we have ribs on the outside surface is no reason why we should not also have ribs on the inside surface.

With the corrugated surfaces, keeping the perimeter of the tank the same, the external surface will be increased somewhat by closing or collapsing the spaces on the oil side, keeping the width of external spaces the same, on account of the increased number of corrugations.

By closing all the internal spaces we might obtain an increase of about 50 per cent in external surface but this would be accompanied by a decrease of about 75 per cent in the internal surface. Assuming that the drop from the oil to the tank, before the corrugations are closed, is six deg., and that the drop from the tank to air is 30 deg., if each of these drops is proportional to the watts per sq. in. on the respective surfaces (which is not strictly correct) the respective drops after closing the corrugations will be 20 deg. external and 24 deg. internal. The sum of the two drops is now 44 deg. as compared with 36 deg. before the corrugations were closed. This calculation is rough and probably gives results somewhat exaggerated but it correctly illustrates the tendency.

Mr. Mershon may object that he did not contemplate closing all of the corrugations, but each corrugation must be considered to a certain extent independently, since the heat which would be conducted through the thin sheet steel tank from the corrugation which is not closed to the one which is closed would be much smaller than at first imagined. Moreover, the reduction in the temperature drop from the tank to the air will be less than would be expected from the amount of increase in the surface, since, not being adjacent to the hot oil, the tank temperature will be somewhat reduced toward the tips of the closed corrugation.

In addition to the above I should like also to offer some remarks on Mr. Pikler's discussion of Mr. Green's paper as follows:

Mr. Pickler's statements regarding mechanical forces and regulation in his discussion of Mr. Green's paper seemed to give a wrong impression. It is the natural tendency of the resistance element of regulation to be reduced with increased capacity, but not of the reactance element. Certainly the reactance in ohms would decrease but the per cent reactance, or reactance volts, tends to increase to the extent that for a given per cent reactance it becomes necessary to break the windings of a large transformer up into a larger number of groups than those of a small one. It is certainly true moreover, that the mechanical forces under short circuit conditions in any given transformer will be reduced by increasing its reactance. It is true, in fact, that if all dimensions and parts of the transformer including the coil supports are increased in equal proportion, all sizes of transformer will be equally safe, except for the affect of the variation in the space factor of the windings which is unfavorable for the larger sizes.

In order to be equally safe, therefore, the larger sizes must be protected by a greater than normal increase, either in the strength of the coil supports or else in the per cent reactance.

R. W. Atkinson (by letter): While the writer wishes to confirm certain of the points brought up by the author, he wishes to take exception to certain of the others. He is glad to see presented before the Institute, the formulae for the calculation of regulation and particularly those regarding the effect of magnetizing current, and would refer to the work done by the Bureau of Standards. The question was taken up very carefully by them, both theoretically and experimentally. They arrived at the same conclusions given by the author. Their results are published in their Bulletin No. 2, Vol. 6. However, the writer does not agree that the cost to the central station of regulation is ordinarily dependent upon the selling price of the power. He also wishes to comment slightly upon the curves in Figs. 4, 5 and 6. It is intended only to mention the above points with a very brief analysis of the reasons for the conclusions.

It is merely desired to call closer attention to the Figs. 4, 5 and 6. The casual reader might draw somewhat erroneous conclusions. In Fig. 5 it is desired to point out that with a purely lighting load where the effect of regulation is most marked, the influence of reactance upon regulation is least noticeable. It is suggested that the various transformers represented in Fig. 6 by curves 1 to 7, could scarcely be considered as having the same general dimensions. No. 7 would have $\frac{1}{4}$ the copper loss of No. 1. Obviously, this would require a very much larger and more expensive transformer unless, of course, some characteristics not mentioned are sacrificed. In case the reduction of the copper loss is at the expense of increased iron loss, the reactance would be reduced in approximately the same ratio as the copper loss. The same comment would apply to Fig. 4 but in a much less degree.

It has been frequently asserted that, on a lamp load, due to a reduction of voltage at the customer's outlet, regulation reduces the power sold to the customer and that therefore the cost to the central station is the difference between the selling price and cost price of this amount of power. Suppose this is true. We ask then why does it not pay to raise the voltage of the system and sell more power, why not do this indefinitely? It is unnecessary to analyze the reasons for not so doing. However, we know that it will pay to make the average voltage of the system approximately that which we would maintain all the time if it were not for regulation. If there is a certain voltage which it would be desirable to maintain uniformly, if possible, it would seem to scarcely require argument that if it is impossible to maintain a uniform voltage, the next best thing is to make the voltage vary *above* and *below* this desirable voltage, and as close to it as possible. The cost of regulation then lies in the effect of this variation of voltage, and regulation is costly just to the extent of the uncertainty and the variation of receiver voltage due to it.

An important effect of the irregularity of voltage is the resultant variation of candle-power of the lamps of the system. In the case of carbon lamps, there is as well a variation of the color of the light. The problem then becomes quite largely one of the psychology of the customer. It is quite certain that if the variation of candle-power becomes serious enough to be offensive, it is very expensive to the lighting company, and is negligible only when not noticeable to the ordinary customer.

The most important effect of regulation is upon the life of the lamps. A lamp burning one-half the time at 109 volts and the other half of the time at 111 volts, has a shorter life than one burning steadily at 110 volts. It is possible to calculate this loss of life due to regulation very accurately from the performance curves furnished by the lamp companies. One thing of interest is that the loss of life varies approximately as the square of the regulation.

The average candle-power and efficiency are not so greatly affected. As a matter of fact, both are slightly increased under the above specific conditions of 109 volts half the time and 111 half the time, as compared with a uniform voltage of 110.

The copper loss of the transformer is so closely related to its regulation on a lighting load, that we may be pardoned for a brief reference to the cost of this copper loss. It needs merely to be mentioned that the cost of power occurring almost entirely at or near the peak, is much greater than the cost per kilowatt hour of an all day load. If this cost is the one cent per kw. hr., mentioned then perhaps the copper loss costs two cents. It is not intended here to show the amount of the difference but merely to call attention to its existence.

There are a great many factors which may influence this problem including those mentioned by the author. Some others are: regulation of the secondary circuit between the transformer and the customer's outlet; the possibility of the voltage of the primary being raised at times of general heavy load on the feeder. The first may be of considerable importance and complicate the problem accordingly. It is sometimes practicable to reduce materially the effects of bad regulation by consideration of the latter.

The writer has attempted to show in a general way that the cost to the central station of regulation is affected not by the selling price of the power, but by the effect upon the life and the candle-power of the lamp and upon the resulting satisfaction of the customer. Where regulation is important, that part due to reactance can always be kept low with less expense than that part due to resistance. The problem of the cost of regulation is an important part of the larger one, that of the cost of the transformer losses, and is a subject which is of great interest to both the designing engineer and to the operating engineer.

C. E. Allen: In regard to Mr. Walden's question regarding the increase in cross section of the cores, it is not clear as to just which figure is referred to, but at any rate the cross section of the core would vary, depending upon its construction. This would be also true of the weight. As to the increase in cost of the transformer I have no figures at hand that are sufficiently accurate to answer this question, but I might add that the weight of copper would increase directly as the increase in the mean length of turn due to the larger cross section, and there would be also an increase in the weight of the copper due to the increase of $\frac{A}{L}$, which represents the leakage path of the flux, in determining the regulation. It would not be an economical design to improve the regulation by increasing the cross section and allowing the number of turns to remain the same.

In replying to Mr. R. W. Atkinson's discussion, the writer appreciates that there is nothing original brought out in the paper, as all the formulæ brought in have been worked out by Dr. Bedell of Cornell University, Mr. Fortesque and various others. The writer has simply made a summation of correlated facts, with a view of showing certain points, which he hoped would be sufficient to justify the Institute adopting a standard method for determining the regulation.

As to the conclusions that might be drawn from Figs. 4, 5 and 6, this depends altogether upon the experience of the reader. The paper is only intended for those familiar with the subject. As to the variation in the power delivered due to changes in regulation, I have been over this subject with various central station engineers, whom I believe represent the leading men in their respective lines, and in all cases they have figured the loss due to poor regulation at the selling price less the cost of delivering the energy to the transformers. Mr. Atkinson asks why it would not pay to increase the voltage indefinitely. While this is no doubt obvious to many, I will answer by stating that there is the question of satisfactory service, which must be considered. Mr. Atkinson has based his statements entirely upon the assumption that only an incandescent lamp load was used. As a matter of fact the importance of the paper at this time is due to the increased day load made up of heating apparatus, etc., the nature of which is similar to that of an incandescent lamp, but where the question of renewals does not enter. On account of this increasing day load, the regulation and copper loss have both become of more importance than previously. At one time the iron loss of a transformer was considered to have a relative value six times that of the copper. This was assuming that full load existed only four hours of the day. To-day the same difference does not exist and, therefore, the value of the regulation and copper loss have been increased.

In taking up this subject the author has not dealt with its influence on induction motors; which is quite as important as the other loads. This is appreciated by central stations serving industrial districts and is brought out in Mr. A. E. Walden's discussion.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

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OIL CIRCUIT BREAKERS

BY E. B. MERRIAM

Introduction. The problem of interrupting an electrical circuit which may be momentarily carrying millions of kilowatts is exceedingly difficult. The greater concentration of power at present under way and the obstacles to be overcome in controlling the huge electrical circuits of these developments are matters which were foreseen by the manufacturers, who keenly appreciative of the importance of these problems, are making earnest efforts to meet the conditions imposed. Unfortunately, it is inconvenient and at times even hazardous to make tests determining the ultimate rupturing capacity of heavy-duty oil circuit breakers, since these tests require the use of the largest power plants now in existence and those responsible for these power developments are rarely willing to loan their equipment for such tests. On account of the variable conditions of service reports obtained are of limited value and manufacturers are forced to accept incomplete information on the action of oil circuit breakers under operating conditions. This state of affairs is greatly improved where the engineers of the large power companies coöperate with the designers and carefully record and freely interchange data relating to all unusual disturbances.

Development. From a small knife-blade switch (Fig. 1) placed in a can containing oil of unknown quality, we have seen the oil circuit breaker rapidly pass through various forms until we reach the present high-voltage, large-rupturing-capacity devices with high grade oil (Fig. 2). They are the result of a natural evolution based upon the conditions imposed by operating men, and also the results of much experimental work on the part of the manufacturers.

Function. The oil circuit breaker interrupts an electrical circuit in oil without producing abnormal disturbances in that circuit, and also confines the destructive effects of the arc to a small volume, thereby preventing its spread to adjacent apparatus and enabling the oil circuit breaker to be safely placed in any convenient location on the switchboard or in the power station. Air-break circuit breakers, owing to the large vicious arcs which they produce, are unsuited for general alternating current circuit-breaking applications. Fig. 3 shows an arc drawn by one of these devices when opening a circuit carrying 800 amperes alternating current at 13,000 volts. This arc, one of many observed, was about 180 in. (4.6 m.) long and rose 140 in. (3.5 m.) in the air, while the same circuit ruptured in oil produced an arc only 9 in. (22.8 cm.) long and with no external disturbance.

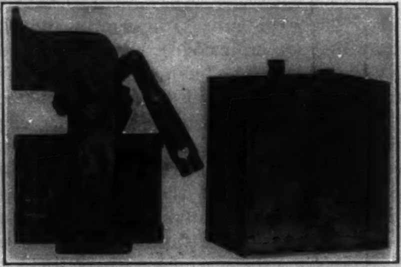


FIG. 1.—Early type of oil-break switch

Action. A distinctive feature of the oil circuit breaker lies in the fact that when the alternating current which is maintaining an arc in the oil passes through zero, at which point the electromagnetic energy is a minimum, the current is interrupted and remains so until the voltage rises to a sufficient value to puncture the oil insulation which has been established between the contacts. As soon as this occurs, the current re-establishes itself and flows for another half cycle. This successive going out of the arc and re-establishing of it thus continues until sufficient insulation is interposed between the contacts to resist the maximum voltage of the circuit, Fig. 4. The insulating layer of oil may be introduced by the rapid parting of the contacts, the confining of the oil to the immediate neighborhood of the disturbance, and utilizing the pressure developed by the arc, or the introduction of fresh oil under external pressure.

Application. While the duties of an oil circuit breaker are to connect, disconnect, and isolate different parts of an electrical system, its most important function is to relieve the system of dangerous overloads or short-circuits which would otherwise prove disastrous to the service. The oil circuit breaker may act instantaneously or have its operation delayed by suitable time limiting devices. By these means, we are able to make them act selectively, and thereby isolate faulty generators, transformers or feeders without disturbing the supply of energy. From these various applications, oil circuit breakers take the names of generator, transformer, group, or feeder circuit breakers (Fig. 5). Generator circuit breakers are preferably ***non-automatic***, as it would greatly disturb the system to have its service interrupted by generators continually disconnecting themselves. Trans-

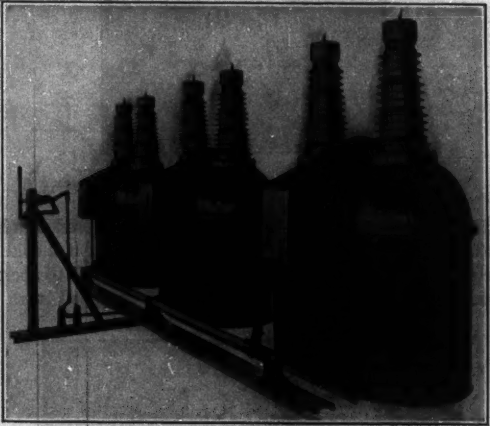


FIG. 2.—A modern high-voltage oil circuit breaker

former circuit breakers are usually equipped with overload, inverse time limit, or sometimes instantaneous differential relays, so that in event of trouble the faulty transformer will be isolated. Group circuit breakers may be set to operate after an abnormal condition has manifested itself for a certain *definite* predetermined time in order to protect the remainder of the system should the oil circuit breaker controlling the faulty feeder fail to operate. Feeder oil circuit breakers are generally equipped with an *inverse* time element so that selective action may be secured in order to isolate faults.

FIG. 3—Arc drawn by air-break disconnecting switch

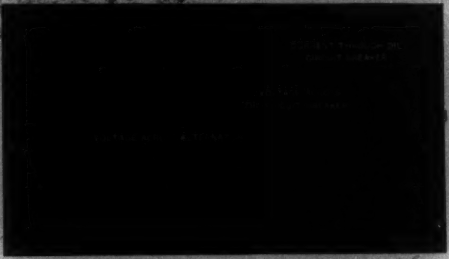


FIG. 4.—Oscillogram of an oil circuit breaker operating under test

Operation. The method of operating an oil circuit breaker whether by hand, electric motor, solenoid, or a pneumatic mechanism, is largely a detail of construction, as any well designed circuit breaker may be interchangeably operated by any of these means, the circuit-rupturing feature being independent of the operating mechanism. For convenience, economy, and safety, large oil circuit breakers are remotely controlled so that they may be placed in fire resisting compartments very near the station bus bars. The control wiring should be installed in such a manner as to preclude its failure under *any conditions* as instances have occurred where circuit breakers have been the cause of the destruction of adjacent control wiring, thus rendering other circuit breakers inoperative.

Inspection and Oil. The severe service to which oil circuit breakers are subjected necessitates the regular inspection of oil, contacts and mechanism, with frequent attention to the general insulation. The oil may be carbonized considerably on a heavy short-circuit, and should inspection indicate this, fresh oil should be supplied. Carbonized oil may be filtered and the moisture removed, after which, it is again fit for use in oil circuit breakers. The quality of oil should also be given careful consideration. Its flash and burning points should be as high as possible—(not less than 180 deg. cent.)—as also its dielectric strength—(not less than 40,000 volts when measured between 0.5-in. (12.7 mm.) diameter disks placed 0.2 in. (5 mm.) apart)—to avoid leakage between contact sor from contacts to ground, and to increase it arc rupturing properties. It should be capable of extinguishing the

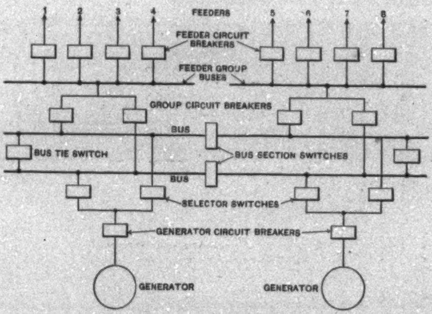

1
2
3
4
FEEDERS
5
6
7
8
FEEDER CIRCUIT BREAKERS
FEEDER GROUP BUSES
GROUP CIRCUIT BREAKERS
BUS
BUS TIE SWITCH
BUS SECTION SWITCHES
BUS
SELECTOR SWITCHES
GENERATOR CIRCUIT BREAKERS
GENERATOR
GENERATOR

FIG. 5.—System of connections, showing location of oil switches and circuit breakers

arc sprung by opening the switch and in doing this the carbon deposited should be a minimum. It should be free from acid, alkali, sulphur, or any other content likely to corrode the metal parts of the circuit breaker. It should be as fluid as consistent and remain fluid at low temperatures.

Insulation. The insulation of oil circuit breakers up to 60,000 volts is well taken care of by porcelain bushings and supports, but above this point, we have to resort to some other means. Here we begin to deal with very delicately balanced electrostatic forces whose peculiarities are only partially appreciated.

Time Factors. The total time interval between the instant the abnormal condition of a circuit is apparent and the instant the circuit breaker is completely opened, consists of the time element of the protective relay, and the time characteristic of the circuit breaker. The time element of the protective relay is the time lapse from the instant the abnormal condition of the circuit is apparent to the instant the circuit breaker trip is energized. It may be variable or constant, depending upon whether the timing feature of the relay is inverse or definite, or it may be entirely absent.

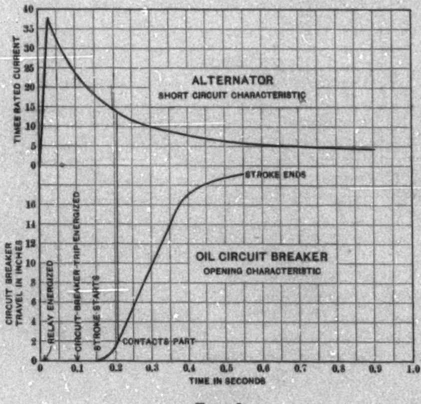


FIG. 6

The time characteristic of a circuit breaker is the time lapse between the instant the circuit breaker trip is energized and the instant the circuit breaker is completely opened (Fig. 6). This is influenced by the time which elapses from the instant the tripping mechanism is energized until the arcing contacts part, and the velocity with which this parting occurs. It should be remembered, however, that the arc is rarely, if ever, drawn the full travel of the arcing contacts of the circuit breaker.

Rupturing Capacity. The rupturing capacity of an oil circuit breaker is dependent upon a number of important elements such as the velocity with which the contacts part, their size and shape, the quality of oil, the electrical characteristics of the circuit, the direction, length and number of breaks, and the type of arc smothering device employed.

FIG. 7.—Modern high capacity, moderate voltage oil circuit breaker

When we consider the velocity of the moving contacts, we see that if they move apart slowly, the arc formed has time to become very violent and destructive, while, if we make this velocity sufficiently high, we reduce the time during which the arc can act, and thus diminish its effects, and increase the capacity of the oil circuit breaker.

The power-factor of the circuit to be opened greatly affects the rupturing capacity of an oil circuit breaker. If the power-factor is less than unity, the voltage is not in phase with the current and this permits the arc to be continued for a longer period.

The amount of current also affects the rupturing capacity of an oil circuit breaker, since upon its magnitude depends the destructive effects of the arc. Hence, anything which will reduce the current will diminish the work of the circuit breaker.

Another feature which we have to consider as affecting the rupturing capacity is the arc smothering device employed. A number of these have been proposed and some are now being utilized, such as baffle plates, (Fig. 7) directed oil jets, oil pressure systems, etc., and it is due to their efficiency that we are enabled to control high capacity circuits and reduce the amount of oil required in oil circuit breakers.

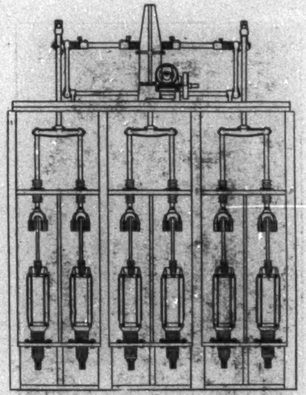


FIG. 8

The characteristics of an abnormal load such as a short-circuit, from which condition the oil circuit breaker is relied upon to relieve the system without interfering with the operation of synchronous apparatus or the interruption of the supply of energy, depends in a great measure upon the size and number of generators actively connected to the system, their internal impedance, and the impedance of the circuits between the generators and the point at which the abnormal load occurs. The enormous currents which have been encountered have led to the consideration of placing external reactance in the loads of the generator units in order to limit the amount of current which may be taken from them on short circuit. The present tendency, is to design generators with large internal impedance, even at the expense of regulation, in order to limit the maximum instantaneous value of the short-circuit current. This will permit generators to be short-circuited without material injury to themselves and greatly diminish the amount of current which the oil circuit breaker is called upon to interrupt, and will thus permit the use of an oil circuit breaker upon a system of larger capacity than heretofore, besides protecting the generators from injury.

DISCUSSION ON "OIL CIRCUIT BREAKERS". SCHENECTADY, FEBRUARY 16, 1911.

B. C. Jamieson: The subject of oil breakers is a very comprehensive one, and, as the title implies, all important is their efficacy as an energy rupturing device. Because of the extent to which they are used and the great amount of power behind them, moderate voltage breakers of high ampere capacity, such as are commonly employed on our large urban distribution system, are the most interesting.

Now with all the technique of operation aside, if the generally recognized limitations of this type of breaker could be removed, it will be conceded that the general switching and protective systems of large power stations would be simplified, and that expensive expedients, such as power limiting devices, would be necessary to a lesser extent. In other words, if it were possible to design a breaker which would instantly remove a member of the system, immediately it became faulty, without injury to the system, we would have the ideal breaker.

The outline of the basic principles, upon which the breakers described in the paper are designed, indicates that the development has been along entirely different lines. Referring to the curves given as the short circuit characteristics of an alternator and applying the switch operating principles, shown therewith, to a large system, consisting of five 14,000-kw. units, it will be seen that the operation of the breaker follows the period of maximum disturbance. The following questions naturally arise, what is to become, during this period of maximum disturbance, of our highly sensitive synchronous system of converters and the like? How much does the general structural reinforcement on the whole bus and switch system, under liability of this current necessary to safely carry these enormous current values, cost? How do we know that these characteristics apply at all when faulty insulation is the cause of the breakdown?

Attention is drawn to these points with a view of inducing the consideration by manufacturers of a type of automatic breaker which will prevent these abnormal current values. The value of such a device, combined with the absence of any assured limitation which might prohibit its development, amply warrants an effort in this direction.

E. M. Hewlett: The main point that does not seem to be appreciated by everybody is that with large generator capacity, switches must be designed to take care of whatever the bus bars will give them. Where the switches have a time limit, the time should be chosen so that you can get on the lower part of the curve shown by Mr. Merriam in Fig. 6, where the current rush is say three or four times the generator capacity. In that way you open the switch at a point where the current is limited.

If it is necessary to open the circuit instantaneously on very large powers, this can be done by making the switch large enough to do the work, but where economy of design in the station is required, you should put in a time limit, and also perhaps reactance, to bring down the work required to be done by the switch. In some cases, you can make the feeder switches smaller and have them take care of a certain amount of power by putting relays on them. This will permit the switch to open up to the power that it is able to operate under. Above this point, these relays will make the switch fail to operate and throw the work back on the main switch, when you can stand the interruption of service for a few moments on account of the economy of first cost of the station.

In reference to the rupturing capacity of switches, Mr. Merriam pointed out the baffle plate in Fig. 7. This baffle plate arrangement holds the oil over the contact and seems to be the simplest and most efficient way of keeping the oil there.

We have under consideration the making of a recording device for some of the large stations, so that we could get a record of short circuits in order to know really what occurs. We hear every once in a while that a switch has opened a very large amount of power successfully, and then we hear that a similar switch has failed on a comparatively small amount of power. There is too much personal element in these reports, so that we are laying out a device in order to learn the actual current conditions at short circuit. This, I think will help a great deal in our research work.

L. C. Nicholson: The principal lesson learned from extended experience in operating oil switches on high power circuits of medium voltage is that it is prejudicial to the successful operation of the switch to cause it to open several short circuits in a short time. Switches of approved type are apt to operate successfully once or sometimes twice within a few minutes, but damage to them will occur if they open severe short circuits in quick succession. This appears to be due to carbonization of the oil in the vicinity of the contacts, rendering the oil ineffective until the carbonized particles have time to settle to the bottom of the switch tank. This settling requires several hours.

As Mr. Merriam points out, a circuit breaker is favored if there is a time lag which prevents its opening on the first rush of excess current. We have found that a time limit of at least two seconds is required to insure the successful opening of a breaker under short circuit conditions.

W. L. R. Emmet: Many years ago I devoted a great deal of my time to oil switches and circuit breakers, but have not followed the subject very much lately, and I do not think I have much to communicate at the present time—the size of some of the circuit breakers recently built is very large, the designs being made to break the tremendous rushes of current which may occur on systems as now constituted; I think the circuit breakers have got about as large as they ought to be, and that further avoidance of trouble should be accomplished by limiting the amount of current likely to go through any circuit, by the use of reactances and other means. This is now being done to a large extent, and I think that the growth of circuit breakers, as regards their size, will probably stop. These devices have been designed with a view to standing very high pressure and keeping the oil in contact with the break when it is possible to do so, but of course there are limits to this possibility and some of these devices which have been very strong, have been blown to atoms by some of the short circuits which have occurred. Many of the gentlemen in this room do not realize the extent and violence of some of the short circuits which have happened in different parts of this country. We had a short circuit in the Fiske Street Station in Chicago, in which the repulsion of the cables ripped many feet of clay ducts out of their masonry setting.

A Member: I would ask Mr. Merriam one point about the necessity of inspecting the oil. He speaks of that point, and I would like to know just how much consequence that has proved to be in practice. That is to say, has it been found really necessary to test the oil periodically, and if so, what does that amount to? I should rather infer from the theory of the operation of the circuit breaker that the chances for carbonization of the oil are so small that the dielectric strength of the oil would decrease very slowly. I should like to know if Mr. Merriam can give any real facts on the point.

R. D. Mershon: I desire to ask of Mr. Merriam, what measurements, if any, have been taken, or experiments made, to find out the effect of temperature alone? I wonder in the case Mr. Nicholson spoke of, how much of the effect is due to temperature and how much to carbonization of the oil. In the case of some of the short circuits, I should think the oil would have a chance to get heated up pretty well, even with one opening of the switch.

C. J. Barrow: Mr. Merriam brings up in his paper the question of power factor, and states that with decreasing power factor the tax on the circuit breaker is very much increased. Yesterday we were talking pretty generally on the matter of placing reactances in bus bars and in generator leads, in order to limit the stresses in the generator and also the tax on the oil switch. It would seem, on looking into the oil switch phase of the matter, that putting a reactive coil in the circuit will not decrease the tax on the switch in proportion to the decrease in current effected.

In the first place the decreased power factor resulting causes for a given current ruptured an increased tax on the switch due to causes which obtain in any low power factor circuit—when the current reaches zero value and arc is interrupted the voltage at that instant available across switch break tending to maintain arc is greatest when power factor is a minimum. The tax is further increased due to the fact that a potential piles up across the reactive coils on short circuit, which when current is interrupted appears across switch break and renders arc more persistent than is the case when generator terminals are short circuited direct. Considering the time-current characteristic of short circuit, Fig. 6, the effect of reactive coils will be to prolong the time required for current to reduce to normal short circuit value, so a switch with definite time lag will where reactive coils are used be called on to rupture a greater current value.

It should be noted in this connection that the falling away of current from a high value at the instant of short circuit to the normal short circuit value results of the " killing " of the generator field by short circuit currents in the armature. Until this " killing " process is complete the original field flux (built up before short circuit) is present in part, but bucked out of the armature windings by excess armature current, and a switch called on to rupture current under such conditions will be under a tax more than proportional to the current ruptured because when current is suppressed a voltage tending to reëstablish it becomes immediately available, the field flux now being free to take its normal path through armature windings. I think this point has a bearing on Mr. Hewlett's remark to the effect that a switch is at times greatly taxed by a system of relatively small kilowatt capacity and again on a larger system operates without evidence of tax.

In talking rupturing capacities it is customary to speak of the kilowatts ruptured as the product of the normal voltage of the circuit by the actual amperes ruptured. It seems to me that the instantaneous current ruptured by the voltage available to maintain it at instant of rupture is more to the point.

On the matter of insulation the insulation of any lead or terminal must provide against puncture and also against " flashover ", *i.e.*, passage of dynamic arc through air around insulation from conductor to ground. In low-tension apparatus the latter consideration is readily taken care of by simply providing an air path, conductor to ground, equal to or slightly in excess of the striking distance of test voltage which the lead must meet. In apparatus for service at 60,000 volts and upwards it is not so easily provided against and considerations looking to the control of " flashover " become the determining factors in the design of high-tension leads. The matter of providing sufficient insulation to resist puncture is in such apparatus a minor problem.

I wish to bring up for discussion the factors which enter to induce " flash-over ". As is well known, an insulating surface will carry a charge. Considering a small area on the surface of a bushing it carries a charge just as would a piece of tin-foil placed over the area. The charge is determined by the location of the surface geometrically with respect to the insulated conductor and parts of ground potential. Likewise, another local area will carry a charge, the potential of which is determined by its position. An analysis will show that the difference of potential between these surface charges compared with the distance of separation is greatest near base (flange) of lead. That is the surface potential gradient considering a path from the flange to the conductor over the surface of its lead is greatest at the flange. It is at this point that such a lead under potential gives first evidence of stress by corona, and later brush discharges and finally by sparking. The passage of a spark brings the points between which discharge takes place to a common potential and thereby increases the stress between these and surrounding points and so becomes progressive. It is a case of series breakdowns and its prevention a problem in potential distribution. The sparks are static discharges only. A spark lengthwise will induce transverse sparks and soon the whole base of lead is covered by a shower of static sparks, which practically "short circuit" the surface over which they strike. These sparks extend towards the conductor as the potential increases, presenting a path for dynamic arc—"flash-over"—at a much lower potential than would be required to produce flash-over in their absence. They are not the result of surface leakage, and are practically independent of the nature of the surface over which they discharge.

It has been the general practice to limit these discharges by interposing barriers (surface washers) in the path of the sparks Within limits this is a very successful expedient. In an ideal design the potential at any point on surface of a lead will be proportioned to its distance from the conductor and the flange. Approximating this condition in a practical way, desired surface potentials can be obtained by suitably proportioning the diameter of the lead throughout its length (when so proportioned resistance to puncture is amply provided for); or surface potentials can be determined by bringing to the surface at intervals ends of foils whose potentials are fixed by embedding in the insulating body concentric with the conductor. The final criterion of the efficiency of a design as regards "flash-over" is the relation which the striking distance of flash-over voltage bears to distance, conductor to flange over surface of lead. A lead having a 30 in. minimum air path, conductor to flange and showing a 300,000 volt test is evidently not handicapped by poor distribution of surface potentials.

H. W. Cheney: Mr. Merriam makes a general statement which I believe will be misleading to some in describing the action of oil circuit breakers. He infers that the current is always interrupted and reëstablished successively in drawing an alternating current arc in oil and that this action is continued until sufficient insulation is interposed between the contacts to resist the maximum voltage of the circuit. This action no doubt takes place when circuits of high potentials are broken on comparatively slow moving contacts. The oscillogram submitted by Mr. Merriam clearly shows that this action took place in the circuit breakers under test when the record was taken. In my opinion it is possible in a well designed circuit breaker to interrupt the circuit abruptly at the zero point of the current wave without successive re-establishment of the current flow by means of rapidly moving multiple break contacts, especially on circuits of medium potentials. I submit herewith in support of this statement some oscillograms made during recent tests under my direction on a 200-ampere circuit breaker.

Fig. 1 shows an oscillogram taken at the point of current rupture on a circuit of 462 amperes, 2360 volts, 60 cycles. The voltage is connected across the line on the load side of the circuit breaker and the oscillogram clearly shows an abrupt interruption of both current and voltage waves.

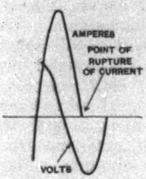


FIG. 1

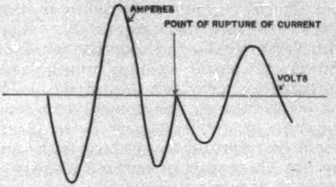


FIG. 2

Fig. 2 shows an oscillogram taken at the point of current rupture on a circuit of 384 amperes, 2400 volts, 60 cycles. The voltage is connected across the contacts of the switch, and the oscillogram shows an abrupt interruption of current wave at the zero point and also a simultaneous establishment of voltage between the contacts.

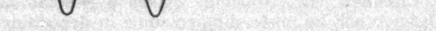


FIG. 3

Fig. 3 shows an oscillogram taken at the point of current rupture on a circuit of 397 amperes, 2320 volts, 60 cycles. The voltage is connected on the generator side of the switch and the oscillogram shows an abrupt interruption of the current wave at the zero point. It also shows that the voltage wave is unaffected during rupture of the circuit.

The circuit breaker which was under test at the time these records were made is provided with auxiliary arcing contacts which remain in contact until the moving element of the switch has attained considerable velocity. The moving element of the switch is comparatively light in weight and is spring accelerated at the point of contact separation so that a very quick break was obtained.

Mr. Merriam points out in his paper that high velocity of the breaking contacts is desirable, and I wish to say in support of this statement that my experience has shown that oil circuit breakers provided with multiple break contacts and high velocity moving elements at point of contact separation give the best results.

In many of the present forms of oil circuit breakers on the market the action in opening depends entirely upon the moving of rather cumbersome bodies through a comparatively heavy oil by means of gravity alone which results in very slow velocity at the point of contact separation, which is objectionable.

I would like to inquire the current, voltage, frequency and power factor of the circuit from which the oscillogram record illustrated in Mr. Merriam's paper was obtained.

A. S. McAllister: It is advantageous to limit the current on short circuit by means of reactance, yet it is undesirable for well-known reasons, to keep the reactance in circuit. Probably it would prove practicable to insert the reactance just when it is needed, leaving it out when it is not needed; in other words, to arrange the circuit breaker so that at the beginning of opening a reactance, on some such device, is inserted in the circuit to limit the current, and then the breaker opens the circuit only when carrying the lessened current.

Chas. F. Scott: We are having a demonstration of the universality of the laws of nature. Self preservation is the first law in apparatus as well as in animals. Yesterday in the consideration of transformers, nearly all the afternoon was spent, not in discussing the relation of the transformer to the power house, or to the consumer, and we were about to be discredited by having a long discussion on transformers without mention of hysteresis when Professor Adams came to the rescue and drew a hysteresis loop on the blackboard, but in discussing the self-preservation of the transformer to find what will keep it from burning up, or getting too hot, and what will keep it from distortion on short circuit.

In the paper on circuit breakers this morning, one of the most interesting curves shows the relation between the current in an alternator on short circuit and the time of opening the circuit breaker, and it was proposed that the circuit breaker wait a fraction of a second until the maximum trouble is over, and then come into action and do its part.

The question as to the time which should be allowed for a safety device to open the circuit is important not only from the standpoint of the circuit breaker, but from that of other apparatus. It may be noted that in Mr. Merriam's paper the curve shows that in certain tests, the circuit breaker contacts parted one-fifth of a second after the relay was energized. If I recall Mr. Nicholson's statement correctly, he is endeavoring to get action within five cycles which is also one-fifth of a second, but he aims to have all operations completed within that interval, namely, only one-fifth of a second is to intervene from the time of the flashover, which may be 100 miles distance from the station, until the apparatus in the station comes into action and short-circuits a station of say 50,000 kw., and the short-circuit has been cleared and normal conditions have again been resumed. This interval is so infinitesimal that synchronous motors and rotary converters are undisturbed in their practical operation.

A general question which is raised is this—how far ahead should the designer look, in designing his apparatus? I mentioned the other evening some transformers which had operated for a number of years until the station was enlarged, and then the coils were found to distort. Mr. Emmet mentioned this morning certain switches which were believed to be perfectly satisfactory, because they operated well on some four or five large generators, but afterwards were found to be inadequate. Lightning arresters which were standard and operated satisfactorily for years were found inadequate when the capacity of power stations was increased. Now, when things are found inadequate, does it mean that the designs are defective and the designer is to be held accountable? Or is the fault due to something else? We certainly cannot look ahead, and be designing all our apparatus now for the time to which our president is looking forward, when the whole country will be interconnected with a 500,000 volt circuit, and practically unlimited energy will be available in each short circuit. It seems to me that the responsibility of the designer is to recognize what the actual specific conditions are, to properly adapt the different parts of the apparatus so as to operate successfully in the plant for which they are made, not necessarily in some other plant or some ultimate plant. He must understand the kind of conditions we have been considering here so that he can foresee and determine what the proper relation and strength of the different parts of the apparatus should be before they are installed, instead of learning them after trouble has occurred.

There is one other little interesting side note to which I desire to refer. The day before yesterday and to-day we have been treated to examples of the oscillograph. I believe all the papers at the Wednesday evening session, and the first paper this morning, are filled with oscillograms. Yesterday, in the papers on the transformer, the oscillograph was entirely neglected, until fortunately some one brought it in to save the day by referring to it incidentally in the discussion. The work of the oscillograph has given some new insight into these problems and makes their analysis a very different matter from what it was a number of years ago.

C. P. Steinmetz: The problem of the oil circuit breaker has always been and still is that of quick opening versus slow opening. If we can hold the contact closed until the generator field has gone down to its normal short circuit value, then we get the safest condition for the oil circuit breaker, but we do not put an oil circuit breaker in a system for the purpose of having the oil circuit breaker safe, but to save the system, and one of the reasons why we have the circuit breaker, is to protect the system from destruction by these enormous short circuit currents. That means that we must open the circuit breaker as quickly as possible to save the system. Where the short circuit current is limited by a long transmission line, so that its value can never be disastrous, then it is safe to hold on, but not otherwise. That means as quick opening as possible. There is a limit to that—it must not be overlooked that the circuit breaker is not there merely to open the circuit, but to open the circuit without causing any damage to the circuit, and if you open too quickly you get an oscillation—a good illustration is that of the condenser shunt in the Rhumkorff coil. Without it, the spark at the circuit breaker causes a slow opening, and you get a little bit of a thin spark, but with the condenser, you get a big spark in the Rhumkorff coil. That is the kind we do not want in our system. We get high voltages and other undesirable impulse forces more than we wish, and there is no need for creating them by abnormally quick opening of the circuit. Hence, we do not want a condenser which takes the momentary current rush away from the circuit breaker, storing it in the condenser, and then returning it into the system to add to the excessive power which at the same time is coming from the gnerator, and doubling up our strains by returning the stored energy into the system. We want a circuit breaker to open as quickly as possible to protect the system, but not quicker than it can open safely to the system, without producing disturbances in the system which may be dangerous.

H. L. Smith: There is one point that Mr. Merriam proposed in the paper, which is much condensed, and that is the question of the rating of oil switches, both for their heating limit and voltage tests. It seems to me it might be well within the scope of the Institute rules to take this matter under consideration.

One point which has been quite largely dwelt upon in connection with the rupturing capacity, which after all is one of the most important factors of the switch, is the question of power factor, and that is interesting from another point of view, although partially covered in Mr. Hewlett's remarks, and that is in different sizes of stations we may get different effects on the oil switches due to the variation of power factor—that is, it is conceivable that some of the smaller stations may give worse conditions than a station of 50 per cent larger capacity, and that, of course, introduces a problem that has to be considered in the selection of the oil switches. The question of rating these switches has in the past been based almost entirely on the results of numerous tests, and presumably these tests have been made at relatively low power factors, consequently it appears that they are along the right line. I think that additional tests at much higher power factors may give us further information, which can be checked over and give us more complete and accurate data for future developments.

E. W. Rice, Jr.: I have not heard any reference to what seems to me to be a rather important factor—it has been stated that it is necessary to have the circuit open very suddenly. In modern central station practice reliability of service is paramount to all other factors. This means that everything is sacrificed to keep the current on the system. It is therefore desirable that the circuit breakers of the generators should be so arranged as to operate only after a considerable period of extreme overload or short circuit has existed. On the other hand, the feeder nearest to the short circuit should be arranged to open in a relatively short time.

It has been suggested, and I agree, that the proper method of operation is to arrange the system so that the current resulting from a short circuit will be automatically limited so that the flow of energy may be kept within a practicable amount. The permissible flow of energy will depend upon the character and size of the system. The best method of limiting this flow of energy in the case of a generator is to increase its internal reactance, but where this is impracticable, to insert additional external reactance in the generator leads. This reactance can be so adjusted as to limit the short circuit and bring it within the capacity of the circuit breaker. Similar external reactances can and should be inserted in important individual feeders so proportioned as to limit the flow of energy to the desired amount. If these reactances are properly designed and installed in a system the circuit breakers can then be provided with time limiting devices so adjusted as to maintain the current upon the system the maximum possible time. Naturally the generator circuit breakers will be adjusted to a longer period so as to open at a later time than the feeders, and as the outskirts of the circuit are reached the circuit breakers can be operated instantaneously as the amount of load which is then disconnected from the system is relatively small in proportion to the total load. Such methods are now being introduced in large alternating current central station practice, and the apparatus, generators, transformers and circuit breakers under such conditions must be made to successfully withstand whatever duty is placed upon them. By such means we can prevent the electrical apparatus from being destroyed and at the same time maintain the maximum continuity and reliability of service.

E. B. Merriam: Mr. Jamieson raises the point that a circuit breaker, in order to render proper protection, should open before the current in the circuit reaches its maximum value. In a number of tests, it has been found that the rate at which the current increases on a dead short circuit is approximately 1,000,000 amperes per second, so that we can readily see the great difficulty presented in designing a circuit breaker to take care of this enormous current increment. The introduction of current-limiting reactances in series with the generator leads tends to limit the heavy current rushes which are present on short circuits and to lessen the strain on the bus and switch systems. This seems to be a much more effective method of protection than increasing the size of the circuit breaker to take care of abnormal conditions unaided.

Mr. Nicholson points out that in his experience successive operation is bad for circuit breakers. We find that the failure of oil circuit breakers after opening successive short circuits is due principally to the ignition of explosive mixtures which are formed from the gases generated by the arc combined with the air in the top of the oil vessel. The amount of these gases is dependent upon the volume of the arc and its duration and these in turn are dependent upon the current which the circuit breaker is interrupting together with the voltage across its contacts and the velocity with which the contacts part. This explosive mixture may be prevented from forming by replacing the air in the upper part of the oil vessel with an inert gas.

It has been our experience that the stresses in oil vessels rarely exceed 300 lb. per sq. in. In cases where cells have been disrupted as described by Mr. Emmet, this has been due not to the failure of the oil vessel but by the mechanical failure of the insulator in the top of the oil vessel. To our knowledge, the oil vessels have never been destroyed except from secondary causes.

The necessity for the frequent inspection of oil is more of mechanical than electrical importance and it is rather difficult to make a statement which will adequately cover all cases. Moisture affects the rupturing capacity considerably more than carbonization, while temperature effects are nullified after sufficient time lapses.

Mr. Barrow points out that the introduction of reactance coils into the circuit theoretically increases the tax on oil circuit breakers due to the lowering of the power factor of the circuit, the adding of the reactive kick to the circuit voltage and the retardation of current decay. However, it must be remembered that the introduction of these devices makes the short circuit current very much smaller so that the ultimate result is to actually diminish the tax on the circuit breaker.

The rating of oil circuit breakers with respect to their rupturing capacity has always been open to more or less discussion and as Mr. Smith suggests, it may be within the scope of the Standardization Committee of the Institute to consider this matter. However, in any case, it deserves careful study and all circuit breaking apparatus should be rated on a common basis.

Some comment has been made with respect to insulation.

On the lower voltages, this is very adequately taken care of by porcelain, but at voltages above 45,000, considerable experimental work will be necessary before satisfactory insulation is arrived at.

Mr. Cheney is quite right in stating that the current is not always interrupted and reëstablished successively in drawing an arc in oil. This action, however, is more apparent on high voltage circuits where the contacts move comparatively slowly. The oscillogram shown in Fig. 4 was taken on an oil circuit breaker when opening a circuit carrying 50 amperes at 6000 volts, 20 cycles, at unity power factor with the contacts moving apart at an average velocity of approximately 13 ft. per second.

Recent tests have shown that it is not undesirable to keep current limiting reactances in a circuit continuously since the loss which they impose is very small and the wave distortion slight.

Mr. Scott brings up the interesting point of how far ahead a designer should look in making up apparatus. Circuit breakers are built to take care of ordinary conditions and future additions to the generating equipment, when radically different, can either be taken care of by current limiting bus reactances or changing over the switching equipment.

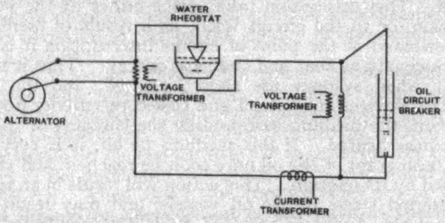
Mr. Lichtenberg's comments in connection with the position of a circuit breaker relative to the generating station is worthy of consideration and in many cases, it is possible to use a comparatively small breaker on a large system if the location is sufficiently remote from the source of energy. Considerable information can be gained from the operation of oil circuit breakers considered as an energy dissipating device as pointed out by Mr. Lichtenberg.

Mr. Collis points out that it is English practice not to have large generator capacities so connected as to permit heavy current rushes at short circuit. There are power houses in the United States, however, whose normal bus bar capacity is approximately 120,000 kw. and it is possible to concentrate the short circuit energy of this system on any one of a number of switches. A conservative estimate of the instantaneous energy available at point of current interruption is approximately 1,000,000 kw. The advisability of concentrating this amount of power is largely a question of the character of the system since the practice of the New York Edison Company is to operate all of its alternators in parallel while the Commonwealth Edison Company of Chicago prefers to group its generating units.

Current increments of 800,000 amperes per second are very common in the United States on short circuits and tests have recently been made where the current increment was approximately 1,500,000 amperes per second. Experiments have been made on switches opening a circuit within 0.01 second with very gratifying results but there has been no opportunity to place these on large capacity systems. The oscillogram shown in Fig. 4 is representative of a number of tests and the accompanying sketch shows the diagram of connections for test during which this was taken. The system of connections shown in Fig. 5 is not intended to show the actual connections of any particular power house but merely to locate the various switches and circuit breakers in order to assist in the discussion of their various functions.

It has been American practice to advocate the use of non-automatic oil circuit breakers for use in generating units since it has been found that where otherwise equipped, they would continually disconnect themselves and seriously interfere with the continuity of service. However, in some cases the generators have been fitted with indicating reverse current relays with marked success.

The theoretical treatment of the transient phenomena during the operation of circuit breaking apparatus requires the consideration of a large number of independent variables. Such a study is very difficult but important and deserves much attention.



Chester Lichtenberg (by letter): In discussing action, the author states that a distinctive feature of the oil immersed circuit breaker lies in the fact that when an alternating current which is maintaining an arc in oil passes through zero, the current is interrupted. There seems to be considerable difference of opinion among engineers concerning this point, but from numerous experiments which we have made, the conclusion has been reached that where the amount of energy is small, the voltage relatively low, and the current not too great, this type of circuit interrupting device may open the circuit at almost any point of the current wave. However, for voltages above 500, and currents in excess of about 200 amperes at commercial frequencies, it has been found that the current is invariably opened at the zero point of the wave. The author also points out that when the current is interrupted at the zero point, it remains so until the voltage rises to a sufficient value to puncture the oil insulation which has been established between the contacts. This is absolutely true for certain conditions of voltage, current, and velocities with which the contacts part. However at power factors other than unity, it has been found that the persistence of the current tends to continue the arc, and prevent the interruption of the current at the end of each half cycle, although there is a tendency for this phenomenon to occur.

Under " Function ", the author states that an oil immersed circuit breaker should interrupt an electrical circuit without producing abnormal disturbances in that circuit. In addition to this very important function, the circuit interrupting device must assist in dissipating the stored electromagnetic energy of the system connected to it, and until this point is fully appreciated by designers and operators, the study of such devices will not advance beyond the primitive stage. This can be readily appreciated when we consider that any electrical circuit will have more or less inductance and capacity in addition to its resistance. Hence every electrical circuit will have more or less stored energy which must be dissipated when that circuit is interrupted. This dissipation takes place either at the point of interruption, or in the circuit itself, as a result of oscillations. When dissipated at the point of circuit interruption it is manifested principally as heat and chemical energy. Thus it may be seen that when systems are short circuited, and the circuit interrupting devices are opened and closed repeatedly upon this short circuit, the medium surrounding the contacts of these devices becomes heated. If this medium be oil, it is very likely that the flash point of the oil may soon be reached, and this will be followed by its ignition. This action will result in an increase of the internal stress in the oil vessels, and may result in an explosion if the device is operated while this condition exists.

In discussing time features, the author divides the total time interval between the instant the abnormal condition is apparent and the instant the circuit breaker is completely opened, into two parts. Most everyone who speaks and thinks of a circuit interrupting device, considers only the first portion of this interval. The second portion, that is, the time lapse from the instant the contacts part until the stroke ends, is equally important. Upon it depends the rapidity with which the circuit is opened. If this time is short, the arc produced is small. But if it is long, the arc is permitted to become very vicious, and may produce oscillations in the circuit. Again, if this time is too short, we will approach the condition of quickly interrupting a highly inductive direct-current circuit, and thus also set up destructive oscillations. Hence there seems to be a definite velocity with which the contacts part, resulting in a maximum efficiency for the circuit interrupting device.

Referring to power factor and its effect upon a circuit interrupting device, we must remember that power factor is really another way of stating the difference in phase that exists between the voltage and the current in an electrical circuit. In addition, however, the power factor indicates the amount of stored electromagnetic energy in the medium surrounding the circuit. Hence, it may readily be seen that when the power factor of the circuit is low, other conditions being equal, the duty of the oil immersed circuit interrupting device is considerably greater than when the power factor is unity. In the former case the stored energy which must be dissipated at the switch when the circuit is opened is considerably greater than in the latter case. In this connection it is well to remember that circuit interrupting devices when placed very near large capacity generating units, must perform much more severe service than when placed a considerable distance away (electrically) from these units. When near the generators, the circuit breaker is called upon to dissipate most of the stored energy of the system, while when remote from the generators, a considerable portion is dissipated in the electrical circuit as a result of oscillations.

A. G. Collis: I notice that the author refers to a circuit carrying momentarily "*millions*" of kilowatts. There is no circuit carrying this capacity in connection with any power station yet designed, and if such a circuit were designed, it would not be advisable to rely on the efficacy of one switch to rupture such a circuit.

The engineer who designed a power station where a switch would be called upon to rupture "*millions*" of kilowatts would be courting disaster. The largest power supply in this country is equal to 35,000 kw., subdivided into groups. Even supposing that a switch on the bus bar side had to interrupt the total power behind it, the maximum rupture in such a case would not exceed 150,000 kw. Then again, the rupture efficiency of the switch would depend on the position of the wave at the moment of opening. The quality possessed by turbo-generators as at present designed for large outputs, *viz.*: the standing up to its work, has been realized in this country. This quality greatly increases the effects of a short-circuit (at present, the generators are not designed with large internal impedance), and switches have been designed to open the circuit as rapidly as possible, as the current increment at the instant of opening may be at the rate of 800,000 amperes per sec. (apart from the fact that the rapid opening of circuit may lead to excessive pressure rises). If, however, the current can be disconnected before it reaches a dangerous value, the rise of pressure may not be excessive. I have designed a switch that will open a circuit under the conditions referred to, and entirely disconnect the supply in less time than one half of the periodic wave, and I have taken oscillograms which show this time element to be 0.01 of a second.

There is another design of switch that will dissipate the rising energy during this time so that abnormal stresses have not to be interrupted during the switching off. This switch is designed so as to completely open the circuit in 0.02 of a second. Oscillograms have been taken showing the results obtained with these switches and in every case, on voltages reaching to a pressure of 25,000 volts, the current has been finally interrupted at the zero point, in the first half of the periodic wave of the circuit. Hence, I doubt the statement that current passes in several waves when switching off.

I give below, some information concerning the records of tests attached hereto, and I enclose diagram of connections, Fig. 10, showing how the oscillograph was connected up.

It is particularly interesting to notice that the potential coil of the oscillogram is connected across the contacts of the switch, and seeing that one side is earthed, the wave of the potential is between phase and earth.

With regard to the oil-switch illustrated in Fig. 2, the development of this form of switch in this country, originated from the water-break-switch, and it is still used in connection with oil switches for direct currents in gassy mines, the water acting non-inductively on the circuit.

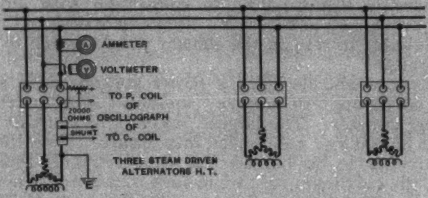


Fig. 10—Alternating current high-tension induction test

The air break switch as shown in Fig. 3 is also interesting, but the oscillograms in Fig. 4 cannot be interpreted as there is *no* diagram showing how the oscillograph was connected up. It is therefore impossible to discuss the relative points of this oscillogram. As a matter of fact, it would appear to be impossible to get a curve such as shown, correctly, unless the current curve is the capacity of the current of the inductive circuit. The potential coil of the oscillogram must be at earth potential, and it appears to me that there is a discrepancy in the relations of the potential and the current curves. In the potential curve there does not appear to be any induced e.m.f. and change of current. This may possibly be due to the fact that the circuit has no appreciable capacity. However, in the absence of information relating to these curves, they cannot be discussed.

With regard to the diagram of connections shown in Fig. 5, I do not think that any engineer in this country would consider such a scheme as referred to. Here, simplicity is of primary importance, and the duplicating of groups, as illustrated would be considered a complication. I may say that grouping, at Cot's Road Station, in this country, led to disaster. The operator did not consider the numbers of the groups, and paralleled all sets of the power station right across the bars, with the result that when the current transformer grounded it short-circuited the switch contacts, which formed practically a short circuit across the whole supply and caused the power station to be shut down for a time.

I do not agree with the author that hand-operated switches should be used for generators, but I advocate reverse relays that will open under a variable power factor—on a small percentage of reverse energy or otherwise, I have used a balanced system of protection.

I notice that the author advocates overload and differential time limit relays for circuits, but it is very difficult to get a discrimination of time values when running on a long feeder so that a short circuit at the end of the feeder shall be relieved without interrupting the entire feeder. Discriminating and overload relays show very little difference in time values under a short circuit condition, and they all invariably come out together.

Regarding protection for transformers, again, overload relays are not considered to be good practice, and in this connection, the high- and low-tension side is interconnected so that should a short circuit or an overload occur in the transformer itself, the transformer will be isolated both on the high- and the low-tension side, simultaneously.

Fig. 6 is not clear to me in respect to the time rated current which is given between zero and 40. I do not know what this figure represents. Apparently the highest peak on this short circuit characteristic appears in less than 0.01 of a time, which, again, is impossible, assuming that the rise is a current rise. If my assumption is correct, it is demonstrated that the highest peak occurred before the circuit breaker trip was energized. Therefore, the system put forward in the diagram proves it to be incorrect.

From the accompanying oscillograms, you will notice that the switch I have designed will open and finally interrupt the circuit in less time, as plotted out in Fig. 6, *viz.*: the circuit breaker trip energized 0.1 of a circuit completes (in my case) interruption in 0.01 of a circuit.

I notice that the stroke of the switch ends in 0.55 of a circuit, which is a dangerously long value, and in fact too long for satisfactory work.

Fig. 7 shows a motor operated switch for the voltage of 60,000 volts. I prefer a solenoid-operated switch, which has a more positive action and is noted for its absence of complications.

With regard to switches for voltages higher than 60,000 volts, I have put forward pneumatic operated switches, so that instantaneous rupture can be effected quicker than by the gravity opening of a solenoid switch.

ALTERNATING CURRENT TESTS

The alternating current tests made were of two kinds:

1. High-tension with inductive load.

HIGH-TENSION TESTS

Arrangement. The arrangement of the high-tension tests is shown in Fig. 10.

The plant consisted of three steam sets driving alternating current three-phase 6500-volt generators of the rotating field type. The sets were first run up in parallel, after which the steam was cut off from two of them, the remaining set driving them as motors.

As it was necessary that the potential coil of the oscillograph should be grounded, one phase was grounded, the pressure consequently being reduced to about $\frac{6500}{\sqrt{3}}$ in order that potential to earth should not be excessive. It varied, however, somewhat, during the tests according to the load. The distance between the generators and switchboard did not exceed 60 yd. so that any effects due to capacity would probably be negligible.

Since there was no return conductor to the neutral point, it follows that the return path for the current was through the remaining two conductors of the three-phase system. The switch in circuit on the high tension tests was of the electrical solenoid operated type, having cone contacts with a break of 10 in. per pole per phase. The whole of the contact mechanism moving in a vertical plane.

The power factor is stated on the diagram, this being the reading taken from a power factor indicator connected up on the circuit. The fact that the diagrams refer to the conditions of one phase of a three phase supply, and also that the voltage is measured between phases and not between one phase and neutral makes it a somewhat difficult matter to draw definite conclusions in respect to the induced pressures due to changes of current, from the records taken.

In all the diagrams relating to the tests on alternating currents, a photographic film must be considered as moving from right to left; that is to say, the current curve which is indicated by the heavy line, appears first, while the voltage shown by the thin line will make its appearance at the moment the current is interrupted.

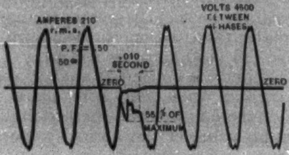
RESULTS OF THE TESTS

See oscillograms Nos. 33, 34, 35 and 36.

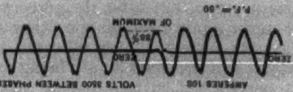
Remarks. Oscillogram No. 33 (210 amperes r.m.s.) shows that the current wave was interrupted as it was approaching zero value. There was an immediate inductive pressure rise, which appears to have been checked very suddenly probably on account of the fact that the impressed voltage wave is endeavoring to establish itself in an exactly opposite direction to the direction of the induced volts. On the other hand, it would appear that it only required a period of time represented by one half of the complete period 0.010 sec. for the voltage wave to establish itself in a normal manner, and it will be noted that the first complete half-wave of the voltage curve reached its normal maximum value.

Oscillogram No. 34 (108 amperes r.m.s.)

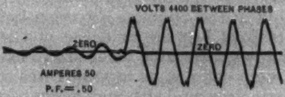
Remarks. In this record the current is interrupted at a point about half-way on the downward curve. It is interesting to note the very sudden reversal of the e.m.f. curve, which again appears to be due to the impressed voltage establishing itself in the direction opposite to the induced volts. In this diagram it will be noted that the half-wave immediately following the rupture of the circuit does not reach the maximum value of the normal voltage wave.



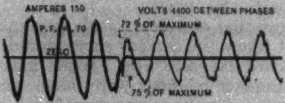
Oscillogram No. 33



Oscillogram No. 34



Oscillogram No. 35



Oscillogram No. 36

Oscillogram No. 35 (50 amperes r.m.s.)

Remarks. It will be noted that the circuit is opened very soon after the maximum value of the current wave has been reached. In this case the first half-wave of the e.m.f. following the rupture reaches the maximum value under normal conditions, probably owing to the fact that the current broken in this case was comparatively small. The increase of amplitude of the current wave just before the circuit is opened is curious. It is the only record in which this phenomenon occurred. The only explanation the writer is able to offer is, that a growth of the current was commencing at this moment. On the original oscillogram the preceding wave appears to be slightly greater in amplitude, and that wave slightly greater than the one preceding it.

Oscillogram No. 36 (150 amperes r.m.s.)

Remarks. The circuit is opened at a point about half-way on the downward current wave, and here again there is a very sudden reversal of the e.m.f. while the first half-wave does not reach the maximum value of the normal wave.

Conclusions (High-Tension Tests)

In all cases the records show that the circuit may open at any point on the current curve, but after the current has died down to zero value, it never again rises on the other side of the zero line. It would appear, in fact, that in all cases, the oil rushes in between the contacts and prevents an arc being drawn out which otherwise might permit the current to rise again after it has passed through zero value. In one or two diagrams, notably No. 34 there appears to be a slight indication of a current wave having passed through the zero point at break, and risen to a very small value in the opposite direction before the current was finally interrupted but the evidence of the current having actually reached any appreciable value after passing through the zero point is not very definite, as in some cases the photographic records are not very clear, and although every possible precaution was taken to ensure that the diagrams should be reproduced as accurately as possible, the author does not wish to lay great stress on this particular point.

It would appear that the final break invariably occurs at or near to the point where the current curve would, in the ordinary course have reached the zero line. When making these tests, voltmeter and ammeter readings were taken, and where figures relating to current and voltage are reproduced on the diagram, these must be considered as the root of the mean square values of the alternating current of e.m.f. The exact maximum instantaneous values reached by the various curves have not been worked out, but in some cases it will be noted that where the normal maximum value is not reached by the voltage wave immediately following disruption of the current, the height of this wave is expressed as a percentage of the height of the wave under normal conditions. In no case do the tests show any abnormal pressure rises. In fact, the inductive rise on opening the circuit in no case reached the normal maximum value of the impressed voltage, but it must not be forgotten that these tests were made with comparatively small currents, the greater current broken being 210 amperes, as indicated on diagram No. 33.

E. Zachrisson (by letter): Regarding the influence of power-factor and of different kinds of loads upon the rupturing capacity of an oil circuit breaker, I wish to make a few statements that may be considered as a modest attempt to attack the subject from a theoretical point of view.

The rupturing capacity of a given oil switch is determined by the size and the duration of the arc formed between the opening contacts. If in the circuits to be opened, there is the same current, but different amounts of other electrical quantities, *i.e.*, of voltage between contacts of resistance, of inductance and of capacity, these factors will be the same until the point when the arc will break for the first time, *i.e.*, where the current passes its zero value for the first time after the opening of the contacts. Beyond this point, the conditions will differ materially for the reason that in different cases the arc has more or less liability to be reformed and that the current, if re-established, will reach different quantities. In the following, only the liability of the arc to be reformed will be investigated to some degree, this quantity being dependent on the voltage between the contacts in opening the circuit, and on the point where the highest voltage appears between the contacts, on the moment of opening the circuit or if later; and whether the oil is much carbonized in the path between the contacts at an instant when there is a high potential stress in the oil.

The investigation may be carried out in following cases:

1. The opened circuit contains merely resistance.

The voltage being in phase with the current, it will at extinguishing of the arc, when the current equals zero, also be zero, and will after $\frac{1}{4}$ cycle equal the maximum value. (See Fig. 1.)

2. The circuit opened contains merely inductance (for instance induction coils or an induction motor with open circuited secondary).

When the current is discontinued when zero, the counter e.m.f. of the circuit will suddenly drop to zero according to the equation

$$E = -L \frac{d\,I}{d\,t}$$

and the voltage across the opening contacts will equal the potential of the supply, which is at its maximum value at discontinuing the arc and will thereafter decrease (see Fig. 1). This behavior is very unfavorable on account of the fact that at maximum voltage the oil is about the same as that through which the current has just passed, and which is therefore carbonized and is not as good an insulator as before.

3. The opened circuit contains inductance and resistance in series.

In this case the theory is about the same as in No. 2. The main difference being that the voltage appearing across the opening contacts will amount to only $E_{max} \sin \varphi$, when φ = phase angle of the circuit. See Fig. 1.

4. The opened circuit contains merely static capacity (not to be confused with "rotary condensers").

There the equations apply

$$I = C \frac{d E_c}{d t}$$

$$E_c = \frac{1}{C} \int I \, d t$$

where E_c = condenser voltage.

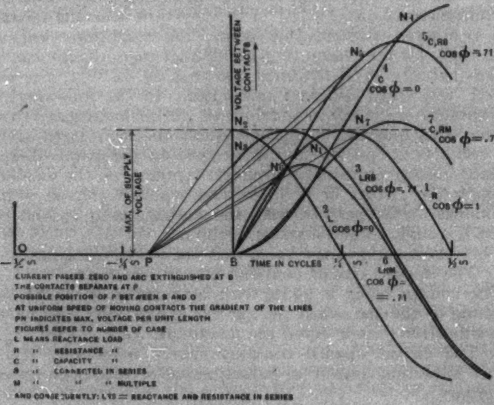


Fig. 1

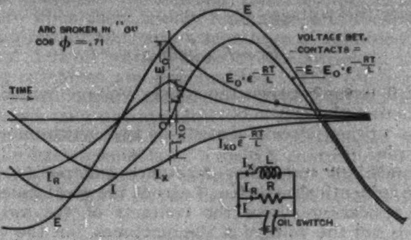
Accordingly, this voltage E_c is not dependent on the current at the instant when the circuit is opened, and because E_c equals the supply voltage in the same moment, no voltage then will exist between the opening contacts. But this electrostatic voltage found favorable in opening the circuit, will after one-half cycle increase the voltage between the contacts to the double maximum value of the supply voltage. This is rather unfavorable because if there is a reforming of the arc at the highest voltage, a heavy rush of current will cross a large space, burning the oil considerably. Fig. 1.

5. The opened circuit contains static capacity and resistance in series.

With the same arguments as for No. 4, it is readily found that the voltage across the contacts also starts from zero and that its maximum value will be $E_{max}\ (1+\sin\varphi)$. See Fig. 1.

6. The opened circuit contains inductance and resistance in multiple.

In this case (see Fig. 1 and 2) when the current passes zero and the arc is ruptured, there will still circulate a current $I_{max}\cdot\sin\varphi\cdot\cos\varphi$ through the resistance and the reactance, causing a voltage $E_{max}\sin\varphi$. This current is decreasing, after the circuit being opened, according to the law


E
ARC BROKEN IN "O"
COS ϕ = .71
VOLTAGE BET.
CONTACTS =
= E $E_O \cdot \epsilon^{-\frac{RT}{L}}$
E_O
$E_O \cdot \epsilon^{-\frac{RT}{L}}$
TIME
I_O
O
I_{XO}
$I_{XO}\,\epsilon^{-\frac{RT}{L}}$
I_X
L
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R
I
I_R
I
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E
OIL SWITCH

FIG. 2—CASE 6

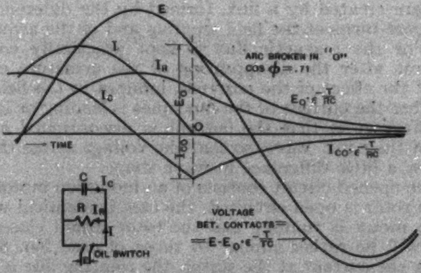
E
I
I_R
ARC BROKEN IN "O"
COS ϕ = .71
I_C
E_O
$E_O \cdot \epsilon^{-\frac{T}{RC}}$
O
TIME
I_{CO}
$I_{CO} \cdot \epsilon^{-\frac{T}{RC}}$
C
I_C
R
I_R
I
VOLTAGE
BET. CONTACTS =
$= E - E_O \cdot \epsilon^{-\frac{T}{TC}}$
OIL SWITCH

FIG. 3—CASE 7

$$I_x = I_{max}\sin\varphi\cos\varphi\ \epsilon^{-\frac{rt}{L}}$$

and causes the voltage

$$E_x = E_{max}\sin\varphi\ \epsilon^{-\frac{rt}{L}}$$

The voltage across the contacts equals the difference between the supply voltage and this voltage E_x.

7. The opened circuit contains static capacity and resistance in multiple.

When the current through the switch (see Figs. 1 and 3) is zero, the condenser is still furnishing the current $I_{max} \cos \varphi \sin \varphi$ to the resistance. This current decreases, after opening the switch, according to the equation

$$I_c = I_{max} \varphi \cos \varphi \, \epsilon^{-\frac{t}{RC}}$$

and causes the voltage

$$Ec = E_{max} \sin \varphi \, . \, \epsilon^{-\frac{t}{RC}}$$

The difference between the supply voltage and E_c is the potential across the contacts.

8. The opened circuit consists of two synchronous machines in multiple.

The machines containing reactance and resistance in series, this case is identical with No. 3 except the great difference of the voltage appearing across the contacts of the switch just in opening is not the voltage of the machines, but the voltage drop in the machines, *i.e.*, the geometrical difference between the e.m.fs. of the machines. Here it is to be remembered that these e.m.fs. are created by a flux, formed by the difference between the ampere-turns of the field winding and of the armature reaction. For the magnetic flux is kept practically constant for some time after the disappearing of the armature current because of the effect of the currents, induced in the field winding.

Whether the current of the machines is leading or lagging, the only difference is that the current is discontinued at different points of the e.m.f. wave, so that the voltage across the contacts will show a little difference in wave shape.

9. The opened circuit consists of an induction motor.

If the rotor is open circuited, the case is identical with No. 2.

If the motor is running and the rotor circuit closed the conditions will be rather similar to those of case No. 8. For in breaking the current at the stator, the rotating flux is kept from disappearing at the same time as the current and is kept practically constant for some time by the currents induced in the rotor circuit. Therefore an e.m.f. is induced, that opposes the supply voltage and thus highly diminishes the voltage across the contacts.

CONCLUSIONS

1. The difference in the behavior of an oil switch at disconnecting different circuits of the same current is not so much due to just the power-factor of the circuit, as to other conditions, such as how much the impedance of the circuit consists of resistance, inductive and capacity reactance and how these are connected, and if the circuit to be disconnected contains rotating machinery or not.

2. A circuit containing only inductance or capacity gives the most difficult conditions for breaking the current, but the reasons why these two kinds of loads are both so very unfavorable are not the same.

3. At a given power factor of a circuit containing resistance and inductance or resistance and capacity, there are very different conditions if there is a series or a multiple connection.

4. The best conditions for a circuit, that contains no rotating machinery, are when there is only resistance, and if capacity or inductance are in multiple, with a resistance of suitable size.

5. The least difficult work is done by the switch in the case that rotating machines are disconnected. The conditions for this work seem to be many times more favorable than when the circuit contained only impedance.

6. It seems possible that connecting a resistance of suitable size across the load terminals of a switch controlling a circuit containing chiefly inductance or capacity, will facilitate the opening of the circuit in spite of the fact that the total amount of current is increased.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

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PROPOSED APPLICATIONS OF ELECTRIC SHIP PROPULSION

BY W. L. R. EMMET

The writer has published a previous paper on the subject of electric ship propulsion and has, in that and elsewhere, given out a good deal of information concerning designs which have been prepared. The purpose of this paper is to describe some of the newest designs of this kind which have been made and to explain some of their features more fully so that their merits may be intelligently considered by engineers who may be interested.

The use of electric motors to propel ships may at first seem inappropriate since with such a method the power of steam must first be converted into mechanical work, then into electricity, and then again back into mechanical work. All of these processes involve appreciable precentages of loss which seem to discourage the undertaking and it is only by the most careful scrutiny of all features that the relative desirability of such an undertaking can be ascertained. Some of the important reasons for the adoption of electricity may however be suggested by the following comparative figures:

	Rev. per min.	Weight lb. per h.p.	Rankine efficiency
12,000 kw. high speed turbine without generator..	1200	8.5	71%
Group of Parsons marine turbines designed to give 28,000 h.p. to four propeller shafts...........	325	42.0	—
North Dakota turbines, two, each 13,000 h.p....	260	—	56%

The large differences shown by these figures are incident to speed, the ship turbine being very large, complicated and expensive, and relatively inefficient, while the high speed machine is very simple in construction, small, and highly efficient. It is therefore primarily for the sake of speed reduction that we turn to electricity as a propelling force.

It has also been proposed to use mechanical gearing for the same purpose and something has already been accomplished in that direction. The use of gearing for such a purpose is however still practically undeveloped and the requirements are such that the extent of its application is still entirely problematical. In the case of electric propulsion no such uncertainty exists. We have proved by application to other arts that certain results can be accomplished in a thoroughly reliable manner and the designs here discussed simply deal with cases comparable with the simplest and most direct uses of electric power on shore.

The comparison of weights and efficiencies of turbines shown by the figures given above apply only to certain conditions and in other cases the comparison might be very different, so that in such a problem every case must be considered on its merits and its merits cannot be judged until all features of design and operation are worked out in detail. An idea of the requirements of ship propulsion may be given by the following rough statement of conditions:

The power required varies approximately in proportion to the cube of the ship's speed. The speed of revolution of shafts must be suited to the power delivered and the speed of the vessel if good efficiency is to be obtained. There is much difference of opinion concerning the possible relations of propeller speed and efficiency. The following table gives an estimate of propulsive coefficients of a large battleship. These figures are ascertained by comparison of several sources of information and should be considered only as a rough approximation.

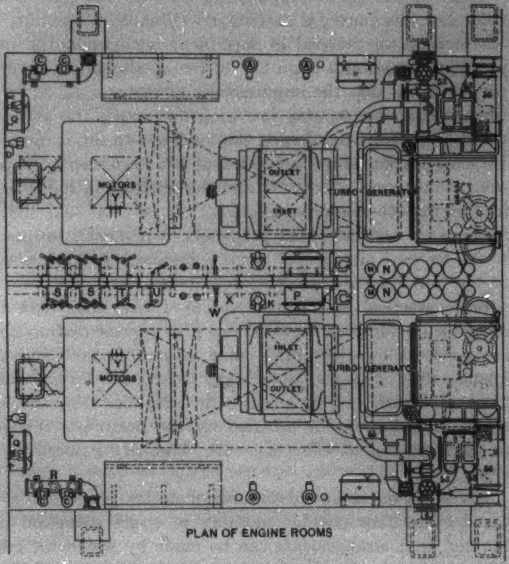
Propulsive coefficients	
Rev. per min.	Two propellers
100	0.56
150	0.532
200	0.507
250	0.485
300	0.470

In all vessels quick stopping and reversal is of great practical value and this quality is particularly valuable in warships. The effectiveness of reversal is dependent both upon the area of propeller blades and upon the torque available for reversal of propellers, so that the requirements of reversal afford an additional reason for desiring low propeller speed, the area of low speed propellers being larger, the tendency to slip is diminished. In some turbine ships, a good deal has been sacrificed for the sake of quickness of reversal and the qualities of different ships in this respect are very different. It may be said that with fairly large and low-speed propellers, a reversing torque equal to 60 per cent of full load running torque will bring a ship up to the best standards of quickness in reversing.

Since practical propeller speeds are always much slower than desirable for turbines, the tendency is to operate marine turbines at speeds below their best point of performance and consequently their efficiency falls off very rapidly with further diminutions of speed. In an electrically propelled ship an excess speed condition can be adopted for the maximum revolutions so that the loss of efficiency with diminishing speeds is relatively less.

One of the important advantages of electric propulsion as compared with other possible methods of speed reduction lies in the fact that arrangements can be made by which the ratio of the reduction is changeable so that the turbine may be run at its most effective speed under more than one condition of the vessel's operation. The possibility of such a change in speed ratio is particularly valuable in connection with warships since such vessels need very high speed for emergency conditions and also need to operate economically at low speed so that their radius of action may be made as wide as possible with a minimum dependence upon coaling stations. It will be seen that these qualities cannot well be combined in a ship whose propellers are driven directly by turbines, even if she is equipped with special turbines for cruising conditions. The importance of high speed being much greater in turbines of small capacity than in large, the cruising turbines which require only a small capacity cannot be made efficient.

In this paper some specific information is given concerning two cases of electric propulsion designs. One of these relates to the apparatus covered by a proposition recently made to the Government for propelling machinery for Battleship No. 35.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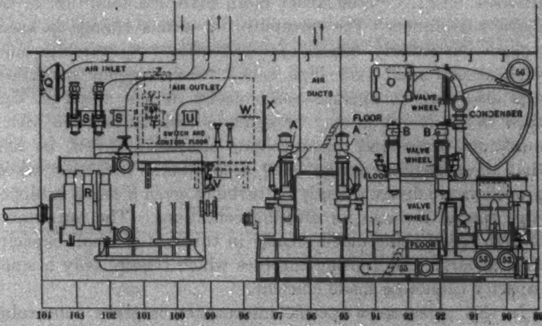
PLAN OF ENGINE ROOMS


AIR INLET
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SWITCH AND CONTROL FLOOR
AIR DUCTS
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VALVE WHEEL
CONDENSER
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VALVE WHEEL
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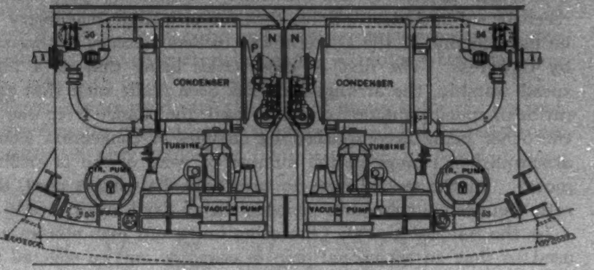
ELEVATION OF STARBOARD MACHINERY LOOKING INBOARD

Plan and elevation of propelling apparatus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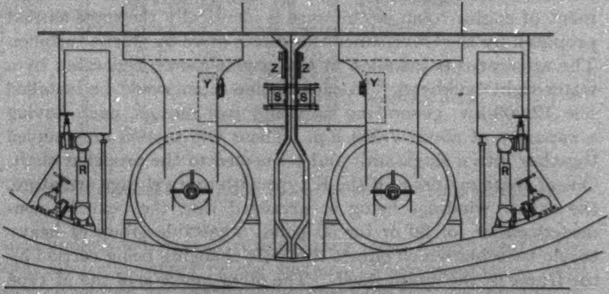
TURBINE
CIR. PUMP
CIR. PUMP
VACUUM PUMP
VACUUM PUMP

SECTION AT FRAME 89 LOOKING AFT

AUXILIARIES

A. Main feed pumps.
B. Fire and bilge pumps.
C. Forced lubrication service pumps
D. Fuel oil pumps.
E. Oil cooler circulating pumps.
F. Pipe insulator circulating pumps
K. Auxiliary air pumps.
L. Auxiliary circulating pumps.
M. Air compressors.
N. Compressed air tanks.
O. Feed heaters.
P. Auxiliary condensers.
Q. Oil coolers.
R. Water rheostat.
S. Motor switches.
T. Generator switches.
U. Tie switch.
V. Pole-changing switches.
W. Hydraulic gear operating wheels
X. Liquid tachometer.
Y. Field rheostat.
Z. Switch panel.



SECTION AT FRAME 104 LOOKING FORWARD

Turbine electric propelling apparatus installed in engine-room of battleship with all auxiliaries specified for direct turbine installation.

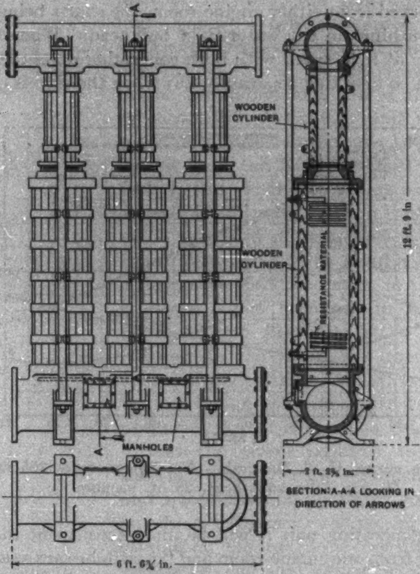
The other applies to the machinery covered by propositions recently submitted to shipbuilders for propelling machinery to be used in one of the Government colliers recently authorized by Congress. The first of these cases being that of a high speed warship, the arrangement has been made such that two ratios of speed reduction could be used, the change from one to the other being accomplished by changes of connection which accomplish a change in the number of poles of the propelling motor. In the second case no such pole changing is used, the ratio between turbine and propeller being fixed at all speeds.

In the battleship, two generating units and four motors are used so that an additional gain in economy can be effected at all speeds by operating with one half of the apparatus in use. In the case of the collier there is only one generating unit and two motors so that all the apparatus is used at all speeds. In the case of the collier however, the speed conditions are very favorable to the turbine and the speed efficiency curve is extremely flat as compared with that of turbines generally used for direct propulsion of ships.

DESIGN MADE FOR U. S. BATTLESHIP NO. 35

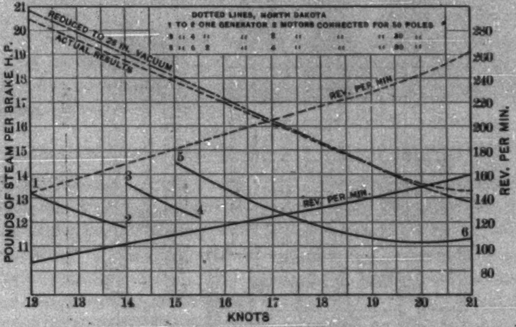
The installation proposed for this ship is shown by the accompanying drawing, which shows not only the electric generating and transmission apparatus but all the auxiliaries which are installed in the engine-room in the Government designs for direct turbine drive. The position of shafts and arrangement of engine-room in this case is identically the same as that proposed by the Government for direct drive by Curtis turbines. The apparatus is installed in two engine-rooms, separated by a water-tight bulkhead. In each engine-room would be installed one 12,000-kw. generating unit and two motors, each having a capacity of about 7,000 h.p. These two motors are coupled together into a single unit and connected to the propeller shaft. One of these motors is of the K type with squirrel-cage armature, the stator windings being so arranged that they can be connected either for 30 or for 50 poles, a suitable group of heavy toggle switches which effects this pole-changing being carried by the frame of the motor itself. The other motor is of the M type with a definitely-wound rotor connected to slip-rings through which an external resistance can be inserted in series. These slip-rings are short-circuited by a very simple and effective sliding spring arrangement. When this short circuit is accomplished the external resistance is entirely cut out. This M motor is wound for 30 poles and with its resistance cut out has exactly the same characteristics as the K motor when the latter is worked with its 30-pole connection.

The resistance used with the type M motor is for the purpose of affording the desired torque in reversing, and these resistances constitute a very important feature of the proposed designs since under conditions of reversal they must absorb nearly the total electrical energy of the system. These resistances have been developed by careful experimenting and are capable of accomplishing the desired result in a very compact space and with very large factors of safety. They are made of non-corrosive material and the heat from the electrical energy dissipated is delivered to the sea water which freely circulates


WOODEN CYLINDER
WOODEN CYLINDER
RESISTANCE MATERIAL
12 ft. 9 in
MANHOLES
2 ft. 2⅝ in.
SECTION:A-A-A LOOKING IN DIRECTION OF ARROWS
6 ft. 6¼ in.

Group of resistances for 7,500-h.p. motor for battleship equipment through the resistance compartments by convection. They are easily disconnected and taken apart or, if desirable, renewed and will afford an entirely satisfactory solution of a problem which has sometimes been very embarrassing in large induction motor installations. The accompanying drawing shows the arrangement of these resistances in sufficient detail to be intelligible.

The switching apparatus is so arranged that all switches can be worked from either engine-room, the shafts being carried through bushings in the water-tight bulkhead. When the ship is operated at high speed with both generating units the engine-rooms will be operated separately but when the ship is operated from one generating unit it will be more convenient to control everything from one engine-room and the switches are so arranged that this can be done, the position of every connection being visible and controllable from either side of the bulkhead. The accompanying tabulation and curve sheet shows the propeller speed, horse power, and water rate of turbines for every different speed of the ship and shows the apparatus which would normally be in use under each condition of speed.



Performance curve, U. S. Battleship No. 35—pressure 265 lb. gauge, 50 deg. fahr. superheat, 28 in. vacuum

The conditions for different speeds are those which will give the best economy and which would ordinarily be used for continuous operation at such speeds but it is possible to vary the speed of the ship up and down with any arrangement of motors

TABLE I

STEAM CONDITIONS—265 LB. GAUGE PRESSURE, VACUUM 28 IN. 50 DEG. FAHR. SUPERHEAT

Knots	12	16	18	19	20	21
Motor speed	87	117	132	140	149	160
Generator speed	1110	895	1010	1072	1140	1220
Shaft brake h.p.	4630	11100	16400	19400	23100	29000
Lb. steam per shaft h.p.	13.2	13.4	11.8	11.3	11.25	11.3

by simply changing the steam admission to the turbines, the only limit being the safe speed and safe carrying capacity of the apparatus. Normally the ship would be operated at higher speeds with two generators and four motors, all of the motors having the 30-pole connection. The turbine speed is then reduced in the ratio of 7.5 to 1, the generators having four poles. When the speed becomes sufficiently reduced improvement of economy can be effected by disconnecting one of the generators and two of the motors as shown by the curve, and when the speed has fallen sufficiently low a still further gain can be accomplished by connecting the remaining motors for 50 poles instead of 30 poles. When this change is made the ratio of reduction is increased from 7.5 to 1 to 12.5 to 1 and a new cycle of favorable speed operation in the turbine is begun. The economy in speeds between 12 and 14 knots is of vital importance in war ships and the very fine economy under these conditions afforded by this design will immensely increase the military value of a vessel so equipped.

Since the power required to propel a ship falls rapidly with diminished speed, and since it is not necessary to maintain any fixed frequency, voltage, or degree of excitation, the magnetic densities of the apparatus can be varied as the speed reduces so as to give the best efficiency consistent with the torque required. With such an equipment the excitation could be derived either from an outside source or partly from an outside source and partly from a direct-coupled exciter. In this case it is proposed to excite from an outside source—the ship's regular circuit—but this excitation can be varied by a rheostat so that the best possible electric efficiency is maintained.

In the installation here described it is proposed to ventilate the apparatus by air from the upper deck. One duct will convey air to each piece of apparatus and another will discharge it outside the engine-room, the apparatus being so designed as to impel the proper amount of air through these ducts. In this and other cases of electric ship propulsion, it might be desirable to ventilate the apparatus by drawing air through it by blowers and delivering the air so heated to the furnaces. Such a process would effect appreciable economy and would probably be desirable. It has not been considered in this case because there was not time to study the practicability of arrangements.

In this battleship installation it is not proposed to make any changes of connection of circuits, resistances, or poles while the current is flowing. Preliminary to all such operations the field switch will be opened. The switches proposed are of the toggle type, not designed to open under load, and are arranged with electric locks so that they cannot be moved when the system is alive. The turbines are arranged with speed governors of the ordinary type which are capable of closing any valves which may be open if the speed rises. The number of valves which can be opened at any time is, however, governed by hand control and the speed governor is incapable of adding to the number so opened. When the field circuit is interrupted the generating unit rises to its maximum speed and runs idle until the circuit is reestablished. In the meantime the desired connections are made and the field re-established, whereupon the generator and motors resume the proper speed relation and proceed to accomplish the desired result.

When these electrical conditions are considered it will be seen that an immense advantage results from the fact that they are not bound to any fixed frequency or voltage. The generator is designed simply to do the work required of it and it is incapable of delivering a current in excess of the safe carrying capacity of any conductor in the system. No kind of wrong connections can result in any burn-out. If a wrong connection should be made it would simply be necessary to open the field circuit and change to the proper connection, and the currents resulting from such wrong connections would not be harmful since the mistake would be apparent and soon corrected. The case is therefore very different from that of an ordinary electric circuit where all sorts of needs must be provided for from a source of fixed potential and where the generating plant constitutes a battery capable of delivering power in indefinite quantities, either for use or for destruction in the case of short circuits or wrong connections.

The following is a list of the weights of the different parts of the installation proposed. The aggregate weight of these parts is probably not much less than that of the turbines alone which would be used for direct propulsion. The generating units in this case however include heavy cast iron bases and there would be a considerable saving on account of the supporting structures which would be used with turbines for direct propulsion. The absence of any system of forced ventilation also increases the weights. In other cases of battleship propulsion which have been studied, considerable savings of weight have been effected and it is believed that with the best arrangements, similar economies could be accomplished in this case.

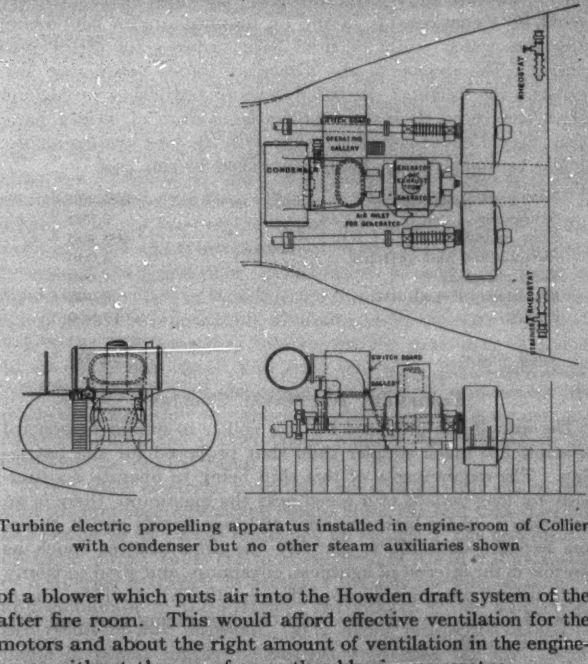
Two generating units	674,000 lb.
Accessories	2,600 "
Four motors	408,000 "
Switchboard and switches	5,000 "
Field rheostats	1,600 "
Water-cooled rheostats	6,000 "
Cables	17,800 "
Total weight	1,115,000 "

EQUIPMENT FOR NAVAL COLLIER

The installation proposed for this collier is similar in general principle but much simpler than that proposed for the battleship. The requirements of this ship being to operate continuously for long periods at a speed near the maximum, there is no particular need for high economy at lower speeds and it therefore becomes desirable to simplify the apparatus as much as possible in the interest of lightness, cheapness, and good economy at the normal operating speed of the vessel which would be about 13 or 14 knots. In this case only one generating unit and two motors are used.

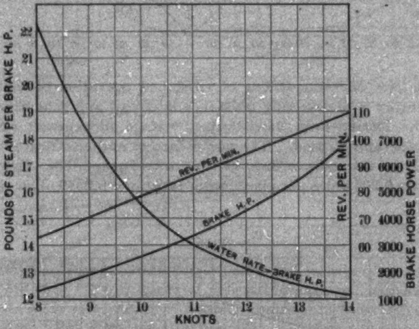
Another difference between this case and that of the battleship is that it is proposed to use oil switches so that changes of connection can be made without the trouble of interrupting the field circuit. When the resistances are in circuit in the motors, either propeller could be reversed independently by simply throwing the lever of an oil switch. This quality of instantaneous reversal would be valuable in a ship of this kind since such large freighters steer very badly at low speeds so that it is very desirable to steer by the propellers in anchoring or docking.

For this collier installation the method of ventilation proposed is somewhat different from that in the case of the battleship. The generator would be ventilated in the same way by a duct from the deck above and another duct to take away the heated air. In the case of the motors it is proposed to take the ventilating air from the engine-room and deliver it to the suction of a blower which puts air into the Howden draft system of the after fire room. This would afford effective ventilation for the motors and about the right amount of ventilation in the engine-room without the use of any other blowing apparatus.


RHEOSTAT
SWITCH BOARD
OPERATING GALLERY
CONDENSER
GENERATOR AIR EXHAUST FROM GENERATOR
AIR INLET FOR GENERATOR
STRAINER
RHEOSTAT
SWITCH BOARD
GALLERY

Turbine electric propelling apparatus installed in engine-room of Collier with condenser but no other steam auxiliaries shown

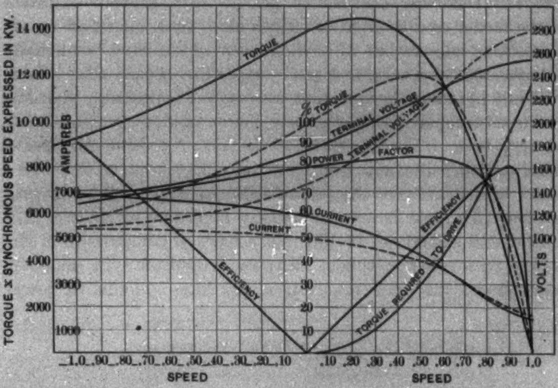
The accompanying curve sheet shows the steam consumption per shaft horse power which would be required with this apparatus at different speeds of the vessel. These results are susceptible of exact calculation since generating units and motors almost exactly similar to those proposed have been repeatedly tested. It is very difficult to get at any accurate estimate of the steam consumption of such a ship when operated by reciprocating engines but all comparisons which have been made indicate that the turbine electric apparatus would effect some economy in steam consumption, although it is probable that the saving as compared with the best engine equipment would not be very large. The demand for electric propulsion on one of these colliers has come from the Navy Department through a desire to demonstrate the practicability of this method of propulsion. The case is not particularly favorable to electric propulsion and should not be taken as a basis of comparison of the system with other methods. Electric propulsion will make its best showing in vessels requiring a very large amount of power or vessels which require a good economy at low speeds as well as at high. High-speed warships or very large moderate-speed liners afford the best fields for its application.



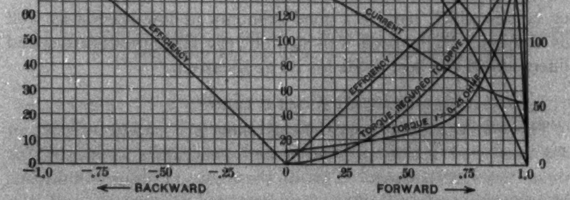
Performance curve, electric drive, U. S. Collier—190 lb. gauge; 0 deg. fahr. superheat; 28½ in. vacuum—displacement about 20,000 tons

Electric Characteristics

The accompanying curve sheets show the characteristics of the combined action of motors and generators proposed for these two installations. Two of these sheets show conditions of operation or reversal with resistances in circuit, and the other shows the conditions in the collier installation without resistance in the motor circuits and with the generator operated at various speeds. From these curves the torque available under any condition of operation and also the current, voltage, and

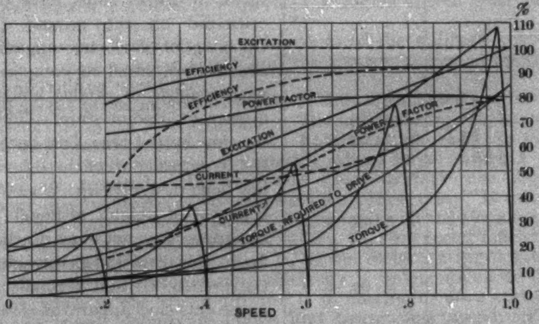


Battleship No. 35.—Conditions of combined operation of motors and generators with reversing resistance in circuit and generators at full speed. Dotted lines show torque, voltage and current when only one generator is used. The power factors and electrical efficiencies are about the same with either one or two generators. External resistance 0.207 ohms per phase, rotor resistance 0.0069 ohms per phase



U. S. Collier.—Showing conditions of combined action of generator and motors with reversing resistances in circuit and with generator at full speed. External resistance 0.75 ohms per phase, rotor resistance 0.025 ohms per phase.

necessary excitation can be seen or readily estimated. No curves are given to show the conditions of operation without resistance in the battleship installation because the characteristics under such conditions are virtually the same as those in the collier and are sufficiently illustrated by the curves given in the case of the collier. These curves show the effect of different degrees of excitation upon power-factor and efficiency. As a vessel so propelled is slowed down, the excitation could be reduced in proportion to the propeller speed and the maximum degree of reduction in excitation will give the best electrical efficiency. From the curves here given, however, the decline of excitation is less rapid than that of the speed, this degree of diminution being chosen so as to give an ample margin of torque under all possible conditions of operation. In practice, whenever the ship is operated under any fixed condition of speed, the excitation should be reduced to the lowest possible point necessary to maintain the required torque on the propeller. Since the margin of torque assumed in the curves given is very ample, the electric efficiencies would be even better than those indicated by the curves.



U. S. Collier.—Showing condition of combined action of generator and motors with varying speed of generating unit and with no external resistance in rotor circuit. Dotted lines refer to constant full load excitation. Full lines refer to variable excitation. Torque curves of motor are given separately for different fixed generator speeds. All other curves apply to normal conditions where speeds of motors and generators vary together.

In connection with this paper which gives specific information concerning two sets of designs, the author has thought it desirabl to give also some figures concerning other cases which have been studied with greater or less degrees of thoroughness in order that an idea may be formed concerning the relative desirability of such methods in connection with ships of different kinds. The accompanying tabulation gives some such figures:

TABLE 2

Case	Displacement tons	Shaft h.p.	Approx. wt. main eng's or turbines tons	Weight of corresp. electric drive	Speed knots	Rev. per min. elec. drive	Water rate elec. drive without aux. lb. per shaft h.p.	Steam conditions
1	19,360	6850	335	135	14	110	12.0	200 lb. gauge. 28.5 vac. dry.
2	25,000	12500	411	237	16	110	11.5	" " " "
3	20,000	3400 17300	435 "	374 "	12 20	87 148	12.85 11.5	260 " " " 50 deg. superheat " " " 28.0 "
4	10,945	2275	102	55	10.5	85	13.0	175 " " " dry
5	9,900	5500	—	133	14.6	114	12.5	181 " " " "

Some of these designs for apparatus to propel ships have been criticized on the ground that the weights of electric apparatus shown were small in comparison with weights of similar kinds of apparatus used on shore. This is to some extent true, first because the structural part of these devices has been designed with a view to economy of weight, although the designers have not gone nearly as far in this direction as it would be possible to do; and secondly because this ship apparatus is rated on a maximum output basis, whereas apparatus for other purposes provides for overload. There have been some further weight economies possible on account of the special conditions relating to the operation of such apparatus. A careful comparison with a number of cases where large apparatus of similar character has been installed on shore shows that on a basis of very reasonable temperature rise, the magnetic weights in all cases agree closely and that these electrical designs are in every respect normal and conservative.

DISCUSSION ON "PROPOSED APPLICATION OF ELECTRIC SHIP PROPULSION", SCHENECTADY, FEBRUARY 16, 1911.

C. P. Steinmetz: Mr. Emmet's paper on electric ship propulsion describes one of the most important and material advances in modern marine work, and more particularly in that highest product of naval engineering, the modern battleship. In the propelling machinery of the ship, the condition which is foremost, before anything else, is to secure the highest possible weight and space economy, and the power economy to some extent is of importance only in relation as it determines the weight and space economy, especially so in military vessels. Any decrease of the weight and space of the propelling machinery means more space for coal, any increase in the efficiency of the propelling machinery means more distance traveled or higher speed, with the same amount of coal.

The two most important requirements of the military vessel are the highest speed in action and the greatest radius of operation at cruising speed.

Of all the prime movers available in ship propulsion, the most efficient one is the steam turbine. The internal combustion engine may sometime be developed. At present its weight is not such as to make it worth considering where large amounts of power are required. However, the steam turbine has some serious disadvantages in its use for ship propulsion. It is essentially a constant speed motor, analogous to the shunt motor, while the reciprocating steam engine is a varying speed machine similar to the series motor, that is, in the reciprocating engine, the theoretical thermodynamic efficiency is independent of the speed, while in the steam turbine it is maximum at a certain definite speed, decreasing above and below this speed. For many fields of ship propulsion, constant speed is suitable, as in the transatlantic liner, etc. But in the battleship, we must have two economical speeds: one very high speed, the speed of action; there we require the highest possible efficiency to get the maximum speed, since the existence of the ship, its life, may depend on its rapid movement. But this speed is used rarely; many ships may pass through their lives without ever being called upon to develop that higher speed except in trial runs, because it is only used in battles. A much lower economical speed is essential for efficient cruising; the cruising speed, about 60 per cent of the racing speed. The operating radius of the ship, and thereby its usefulness, depends on the efficiency at this speed, and maximum efficiency thus must be reached at this cruising speed as well as at battle speed.

A constant speed machine such as the turbine, is not suited to operating at very different speeds with equal, and highest efficiency, but an electric motor can do that. We can have an electric motor operating with equal efficiency at two or more speeds, and therein lies one of its advantages.

At first sight the method of interposing between the turbine and propeller shaft an intermediate link, the generator and motor, appears indirect, and therefore less desirable than the direct drive of the propeller. However, such objection does not apply where electric power is used, because after all, all applications of the electric motor are indirect, intermediate links between a prime mover and the load. The electric motor does not generate power, but merely delivers the power which is generated somewhere else. It is an indirect method of supplying power where it is being used. That it is used to a rapidly increasing extent, is due to the superiority of the electric drive in its flexibility, convenience, reliability, etc. For instance, in the case of long distance transmission. We cannot bring the water power to the city, but we can take the motor to the end of the transmission line. We cannot put a steam engine at every group of machines, but we can have a highly efficient steam engine or turbine driving the generator and have a motor at every shaft. In ship propulsion, the advantage which we gain by the motor are its flexibility, especially regarding speeds. The economical speed of the steam turbine and the economical speed of the ship's propeller are widely distant, and it is not possible to compromise between the two and get both speeds together without a material sacrifice of efficiency, as the history of all steam turbine ships has shown.

The steam turbine is essentially a high speed machine, since steam is the operating medium in the turbine, and the velocity of rotation must be related to the velocity of the medium. The velocity of steam expanding from boiler pressure to a vacuum is nearly 2000 meters per second, over a mile per second. This velocity is from two to three times as great, the kinetic energy from four to nine times as great as that of the modern high velocity rifle bullet. It is a speed which would carry us across the continent from New York to San Francisco in less than one hour. This speed we have to control in the turbine engine. We break it up into a number of steps. But we have to realize, when we use a number of expansion steps, we subdivide, not the velocity, but the energy which is proportional to the square of the velocity; to get down to low velocities in this manner, means very many expansion steps, and a correspondingly low space and weight economy, and also lower power efficiency. That is, the low speed steam turbine is inefficient.

Some data on efficient propeller speeds are given in Mr. Emmet's paper. This data to my mind does not yet represent the actual conditions because they give the propeller as operating under normal conditions. We know that in any apparatus when you compare the different possibilities, it is not only the normal condition of operation, but the emergency or abnormal conditions, which are the criterion on which we have to rely in judging reliability, etc. The greatest emergency in ship propulsion is the rapidity of reversal, when the propeller is called upon to give the maximum possible torque to stop the ship as quickly as possible, because the existence of the ship may depend on the rapidity of stopping. This is the condition where the difference between the high-speed small propeller and the slow-speed large propeller is greatest, because the maximum thrust which the propeller can exert, depends on its diameter, and is a function of the square of the diameter of the propeller, that is, the thrust per unit area of the propeller, positive at one side, negative on the other side, is limited. On the negative side, the suction thrust can not exceed the pressure exerted by the atmosphere and the head of water, and is between one and two kilograms per square centimeter. If we try to drive faster, a vacuum is created, and the propeller does not act properly on the water any more, looses its grip, what is called cavitation. The thrust at which cavitation begins, is depending on the square of the propeller diameter, that is, the area of water acted on by the propeller, and here it is where the low speed, large propeller shows its greatest superiority in its effective operation in reversing, accelerating, stopping. Thus, the high-speed propeller is inferior in efficiency, and control. As the result, in its application directly to the ship's propeller, the steam turbine is greatly, and in slow-speed ships, as colliers, almost hopelessly handicapped, and at the best, in high-speed transatlantic liners, gives a performance greatly inferior to that, with which we are familiar in the high-speed turbines of all electric generating stations.

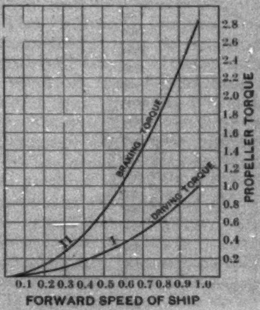


FIG. 1

One of the most important advantages, which the use of the electric drive holds out, is the possibility of a much more rapid stopping and reversing of the ship, more rapid than the steam turbine or even the reciprocating engine can give. The curves given in Mr. Emmet's paper show a full speed reversing torque of the motors as 133 per cent of the torque required to drive the ship forwards at full speed. It is obvious that in a flexible apparatus, such as in the induction motor-generator, we could, by changing the rotor resistance, increasing the generator excitation, and draining the boilers of steam by feeding momentarily an excess of steam into the turbines, still greatly increase the reversing torque, to practically any reasonable value, if it were needed. But the paper states that it is not needed, since experience has shown that the condition of reversal is satisfied by a reversing torque equal to 60 per cent of full load torque. This appeared somewhat startling, and it took me some time to grasp its significance.

The paper shows the torque required for the propulsion of the ship, as function of its speed. This is reproduced as *I* in Fig. 1, in fractions of full speed torque.

The torque required to drive the propeller backwards for different forward speeds of the ship, is shown, approximately, as taken from tests of propeller models, by curve II. It is given in fractions of the torque required for full speed forward drive.

As seen, at full forwards speed of the ship, it would take nearly three times full load torque, to start the propeller backwards. The torque of 60 per cent of full load torque, which is claimed to be sufficient for reversal, is reached at a ship's speed of 46 per cent of full speed. That is, with a reversing torque equal only to 60 per cent of full load torque, the propeller could be started backwards only after the ship has spontaneously decreased in speed by the water friction, to less than half speed.

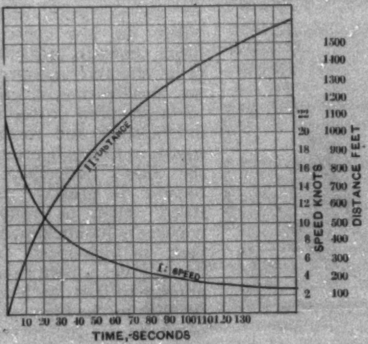


FIG. 2

If then 60 per cent of full-load torque is sufficient for reversal, it seems, that the time required in stopping and reversing the reciprocating engines or turbines is so long, that in this time the speed of the ship has decreased greatly, and the ship traveled forwards a considerable distance.

In curve I of Fig. 2 is given the calculated deceleration curve of a typical battleship of 20,000 tons. As seen from curve I of Fig. 2, the initial deceleration is very rapid, and 46 per cent of full speed is reached after 24 seconds. During this time, the ship has traveled 580 ft., as seen from the time distance curve II of Fig. 2.

With a reversing torque equal to 60 per cent of full torque, the ship would thus have traveled 580 ft. before the propeller begins to retard. With the electric drive, it should be possible to reverse the motor in emergencies in five seconds or less, that is, after the ship has drifted only 150 ft. or less. Then a reversing torque of 1.87 times full load torque would be required, and the drift of the ship would be reduced by over 400 feet.

It thus seems, that the introduction of the electric drive would not only give an increase of space, weight and power efficiency, and thereby an increase of the maximum speed and an increase of the cruising radius of the ship, but also a material increase in the promptness of control, especially under emergency conditions, as exemplified by a great increase of the rapidity of stopping the ship from full speed.

Gano Dunn: The subject of the moment is another demonstration of the old adage that the longest way around is often the shortest way home. We saw this first demonstrated when it was proposed to introduce electric drive into factories.

There was no dispute that a revolving shaft would more efficiently transmit a given power to a given place, yet as a system of distribution the electrical method was far ahead in efficiency and had many other advantages besides.

The Heilmann locomotive was a second demonstration. This locomotive might be described as one of Mr. Emmet's ships on a railroad track. It was an attempt to dissolve the affectionate connection that for so long had existed between cylinders and wheels and the reason it has not been heard from, as I believe Mr. Emmet's ship will be heard from, is it did not have the advantage of turbine efficiency and cost in its prime mover.

In the ship of the paper there are no cylinders to be divorced, the turbine and propeller each chooses its own condition of maximum commercial efficiency, high speed for the one and low speed for the other. Independence of direction of rotation, advantages of remote control, and remarkable facility of adjustment are linked together by an electromagnetic connection that renders these advantages possible.

It is advantages like these that stand out so strikingly in Mr. Emmet's paper and not solely the advantages of efficiency that are behind the enormous and rapid growth of electrical applications. This growth is because we can do things by electrical methods that we cannot otherwise do.

It might be said that until the present generation our only means of transmitting power was matter. We had mechanical systems and the distances over which they could operate and the things they could do, were limited, but now we substitute ether and receive such lavish endowment in increased flexibility, adaptability and efficiency that we are affecting the character of civilization.

It is unfortunate that turbines and propellers are most comfortable at the opposite ends of a wide range of speed.

An enormous amount of attention has been given to the development of a mechanical gear for connecting them, and efforts have been turned in the direction of making this gear more or less flexible.

The electromagnetic connection which Mr. Emmet's paper describes is flexibility in perfection. It gives that soft and fluffy contact between the power and its work that the flexible gear men are trying so hard to get in their mechanical devices.

It is no small pleasure as electrical engineers that we see a third important mechanical problem solved by electrical means, and as usual, the solution solves more than the problem. We are presented with advantages of control and adjustability that we were not looking for.

Maxwell W. Day: It is characteristic of Mr. Emmet to take large steps in advance, rather than small ones, and this case is not an exception as the following facts show.

There are three small vessels in Europe of 1150 tons and less, using internal combustion engines with generators and electric motors, two of these vessels being arranged with magnetic clutches so that reversing and manouvering can be done by the electrical equipment, but at full speed the magnetic clutch is thrown in and the propellers are operated directly from the engines.

The German Navy has a salvage ship for submarine torpedo boats operated by steam turbo generating sets and electric motors. This vessel is used for charging, docking, and raising submarine torpedo boats.

In our own country the two principal cases are those of the Chicago fire boats, equipped with turbine driven generators and electric motors, also operating on the Leonard system. These boats can be perfectly manouvered by the pilot without the use of any signals to the engineer. With the electric arrangements proposed by Mr. Emmet for handling the largest vessels, the time for stopping and reversing the propellers will be very much reduced from the time required in the present steam practice. I noticed particularly the long time required for this on the Steamer Harvard, as the signal from the pilot must be answered by the engineer, one throttle closed and another opened in order to reverse the propellers.

W. B. Potter: It has been suggested that it would be of interest in connection with Mr. Emmet's paper on electric drive as applied to marine service, to mention something concerning electric drive as applied to self-propelled motor cars using a gas engine for prime mover.

The gas engine and the steam turbine have a similar characteristic in that both are materially affected by a decrease in the number of revolutions. For reasons of economy with respect to weight and fuel consumption, it is desirable that the gas engine should be no larger than necessary to deliver the power required to drive the car at full speed. The electric drive provides a means of delivering the full power of the engine from the moment of starting up to full speed with a tractive power inversely proportional to the speed and limited only by the slipping of the driving wheels.

It might reasonably be asked why a mechanical drive would not be as suitable for these large cars as for automobiles, especially since the cars run on a smooth track with much less friction per ton than rubber tired vehicles on an ordinary roadway. The value of the electric drive lies principally in its ability to provide the high tractive force required to accelerate the greater mass of the motor cars, which weigh from 35 to 50 tons. To do this with mechanical drive and utilize the power of the engine as advantageously as with electric drive, would require a prohibitive number of gear changes.

The maintenance of the schedule is an important factor in the operation of a motor car and to accomplish this, it is very desirable that the power of the engine be used to the best advantage during acceleration. The generator, which is directly connected to the engine, is provided with a field control regulated by a switch operated by the engineer. This switch is located within the controller which also has contacts for connecting the motors in series or parallel and for reversing the direction of movement in the manner usual on a trolley car.

Reliability of operation with respect to the transmission of power from the engine to driving wheels, is well insured as the apparatus and devices used are similar to those on electric cars.

The cars are usually from 56 ft. to 70 ft. long and are divided into compartments to provide so far as the service is concerned, a complete train within a single car. The supply of fuel carried is sufficient for a run of approximately 200 miles.

Electricity has been generally considered in connection with transmitting power to a distance but its advantages as a flexible connection between the prime mover and utilization of the power, do not seem to have been fully appreciated. In both marine and railway service I believe the electric drive has an important field of development.

H. A. Mavor (by letter): The propositions made by Mr. Emmet and the calculations there anent are of the greatest interest and it is reasonably certain that the claims which Mr. Emmet makes for economy can be fully realized, but the machinery arrangements shown in the paper are liable to hostile criticism from marine engineers. They would doubtless be justified in saying that while the arrangements shown would be perfectly feasible and probably quite satisfactory on a land installation, at sea the use of such appliances in the manner described and on the scale proposed would be a somewhat bold experiment. The writer of the paper would doubtless be the first to admit that confidence in such arrangements must grow with experience.

Apart from any objections which may be made by marine engineers it is evident that in laying down a scheme for marine propulsion the simplest possible expedients should be adopted and for this reason it appears to the present writer that all arrangements requiring the use of delicate instruments of precision, or of resistances to absorb large powers, or of subdivisions of the plant and arrangements thereof which involve running generating units in parallel, are to be scrupulously avoided. The general objects to be attained may be stated as follows:

1. To provide a simple, trustworthy, and economical means of adapting the power generator to the propeller so as to permit of differences in speed essentially associated with the different characteristics of the power generator and the propeller.
2. To provide means for changing the speed ratio between the generator and propeller so as to permit of the power of the generator being developed under the most favorable conditions at all speeds of the ship. This change of speed ratio should be accomplished without interfering with the efficiency of the apparatus under full speed conditions or with the satisfactory design of the equipment.
3. To provide a ready means of reversing the direction of rotation of the propeller without changing the direction of rotation of the power generator.
4. To provide means for applying the power of one or more engines to one or more propellers so that the power generating units may be so disposed as to give the highest efficiency and when they are not required they may be stopped.

This object should be attained without the necessity for paralleling the electric generators.

Mr. Emmet's proposals appear quite satisfactory in respect to object No. 1.

In respect to object No. 2 it does not appear that the pole-changing devices can be reduced to the simplicity necessary for satisfactory operation instantaneously at the word of command or signal from the bridge.

The third object Mr. Emmet appears to have satisfactorily attained.

The fourth object is more difficult of attainment by ordinary methods. The writer believes he has solved the problem by two methods which have been described by him in a paper read before the Institution of Civil Engineers in London, December 1909. For most purposes where there is more than one generating unit, in the present writer's opinion, the motor described in that paper, meets the conditions in an extremely simple and effective manner. Each motor has as many windings as there are power generators on the ship. These windings are absolutely normal in character and the pole numbers are so designed that they all suit the same slot number. At full power each generator feeds into its own winding and if the windings are so arranged in respect of pole numbers that they are mutually non-inductive the generators do not require to be synchronized or run in parallel and may be switched in anywhere near the proper speed. The pole numbers of the several windings need not be very far apart but of course they must all result in association with generator periodicity in the same shaft speed.

The writer has built and equipped a small vessel to illustrate the principles on which a plant of this type can be worked and he has been astonished to find how difficult it is, even with so simple an equipment, to keep down the number of parts and to preserve the straightforward character of the work. It must not be forgotten that while in many respects the marine engineering problem is much simpler than ordinary transmission of power on land and that many of the difficulties with which the land engineer is faced are entirely eliminated at sea, there is one prime requirement which must be kept in hand and every necessary artifice adopted to preserve it, *viz.*: That the engineer shall be able instantaneously to produce the result called for by the working of the ship. He must not have to stand and wait till his plant is run up to synchronism before he can close his switches. The few seconds required to do this may give time for a collision to occur or for the ship to go ashore.

Experience in the use of the "multiple motor" equipment has already shown that the alternating current applied in this way is beautifully adapted to the purpose and is infinitely superior to any conceivable continuous current arrangement. To bring out this point would require a full description of the machinery and trials, and as the experimental vessel has only done preliminary trials the time has not yet come for describing them, but the results so far are very encouraging. There does not appear to be any need for resistances in the secondary circuit.

C. H. Peabody and H. G. Knox (by letter): This paper by Mr. Emmet, on account of his previous experience in the Navy and his present position in a great electric company, challenges both our attention and our appreciation of his attempt to solve one of the most difficult engineering problems of the day.

The limited application of steam turbines to the direct propulsion of ships is well understood—by none better than by turbine builders. To extend their range, a number of devices, mechanical and electrical, have been proposed; though none has yet won its way to general acceptance, it appears likely that some or all may succeed when applied to merchant ships.

The most difficult problem of all is that to which Mr. Emmet has turned attention, namely obtaining a good steam efficiency for battleships, both at full speed and at cruising speeds. A mechanical reduction gear, if applicable to the enormous power developed on battleships, might give some amelioration of conditions for both services, but would be subject to the mechanical compromise now accepted both for reciprocating engines and turbines. None of the several electric devices preceding that offered by Mr. Emmet, such as the use of induction generators, frequency changers, and induction motors in concatination, appear to be adapted to warships, for though they offer several speeds, there is no provision for that nice adjustment of speed required for station keeping. The combination of pole changing coupled with rotor resistance, and direct control of the speed of the turbines proposed by Mr. Emmet, appears to meet this feature completely. This and his estimated steam economy at all speeds makes his proposition exceedingly attractive, especially as he claims for it simplicity, strength, and light weight.

Naval architects generally have comparatively limited acquaintance with large electrical undertakings involving the use of alternating currents, and may not appreciate the precisions that can be assured to computations of electrical efficiencies and steam economies of turbo-generators; they can, however, understand the weight that must be given to the results offered in this paper. They entirely appreciate the advantages of choosing favorable conditions for the propellers.

Sea-going men may look askance at a voltage of 2700 proposed by Mr. Emmet as a maximum in his device; but this is only a little in excess of standard voltages in common use for all sorts of purposes in all sorts of places. In reality the conditions on shipboard are comparatively favorable especially in the engine room. The leads carrying the great currents at high voltage are short and can be completely protected so as not to call for apprehension; certainly not so much as steam pipes with 260 lb. pressure.

The resistance units may need to be demonstrated under actual conditions, especially to show that convection currents in the cooling water are sufficient to take care of the heat generated at an enormous rate, even though it be admitted that the action is momentary; attention should be called to the fact that the resistance grids displace a considerable volume in the cylinders containing them, and also impede the circulation. Perhaps a circulating pump may be desirable until experience has been had.

Mr. Emmet emphasizes the advantages of a large propeller and a good torque for stopping and reversing, and estimates that 60 per cent of the full load torque would be sufficient. He doubtless has in mind that the torque should be applied gradually or there may be danger of excessive stresses in the propeller blades.

After what has been said concerning precision of computation of electric efficiency and steam economy, we must not carp at his estimated steam consumption per shaft horse power; they are certainly very favorable when from them allowance must be made for frictional and electrical losses. In this connection it may not be out of place to call attention to the reported water rate of the *Harvard** which used 14.7 lb. of steam per shaft horse power in the turbines. This may be allowed to emphasize the objection to the trial of Mr. Emmet's schemes on a collier, when, truly, it may demonstrate its practicability, but not its efficiency; especially as tested against a turbine with mechanical reduction gear.

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* Trans. Society N. A. & M. E., 1908.

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VOLTAGE REGULATION OF GENERATORS

BY H. A. LAYCOCK

The voltage regulation of generators was recognized to be an important factor in central station operation as early as the first installation of the Edison bi-polar generator. At the time these generators were first installed it was found that owing to the poor regulation of the prime movers, which were very poor regulating engines, that with fluctuating loads lighting was not very satisfactory when connected to the same dynamo which operated power loads, and in order to produce constant voltage a regulator, which was practically an automatic rheostat having the rheostat switch controlled by a solenoid, was designed.

Since the days of the Edison bi-polar machine, with the advancement in electric generators, voltage regulation has become more and more an important factor, and in order to obtain this regulation some of the first alternators were designed with compounding fields. This was the old type of revolving-armature machine in which the compounding was affected with a series field or current transformer action—the additional turns on the auxiliary field increasing the voltage as the load came on. While this alternator was fairly close in regulation if the load was not too severe the speed regulation was still a factor over which this type of machine had no control.

Various devices have been exploited with a view to obtaining voltage regulation, but most of them have been based on the principle of the automatic rheostat, which has been unsuccessful due to hunting and also to the fact that in order for a rheostat to come into operation the voltage must first vary, and of course the moving element being slow the voltage would vary considerably before the regulating rheostat would operate. This was little better than hand control.

In order to obtain good regulation on the standard alternators of to-day it is necessary to take into consideration the following conditions:

First, the inherent regulation of the alternator. If the alternator is a good inherent regulating machine and is one which is designed at fairly high saturation with a given excitation it is supposed to regulate within 8 per cent with a constant speed; but again, the speed changes are not taken into consideration. In order to obtain the best voltage regulation from an alternator without an automatic regulator the exciter is also run at a high density and is usually compound-wound so that it will either give the same excitation from no-load to full load or will be slightly over-compounded to take care of the increased load, and will thereby compensate in a measure for the drop or rise in voltage as the load is varied. Probably one of the best voltage regulating machines was the inductor type alternator, which had a long magnetic path and very high density, in which the time element was six to eight times that of our present revolving-field type of generator, with a non-inductive load this alternator would probably regulate for voltage better than the revolving-field machine, but with an inductive load which required a much broader range in excitation the inductor alternator was not satisfactory. The reason this type of alternator was unsatisfactory in regulation was due to the fields requiring a very broad range in excitation, and with an inductive load the excitation was from two to three times that required by the revolving-field type of alternator, and with an automatic regulator which increases the field excitation according to the variation in load, it was a difficult matter to regulate this type of generator.

Second, in voltage regulation the exciter is also a very important factor. For example, if an exciter is designed at very high density the time element required to change the voltage from one point to another is so long that the voltage regulation may be materially affected, and in order to have the best combination for voltage regulation an alternator should require a range in excitation from no load to full load, with approximately 80 per cent power-factor, of a ratio of not more than one to two, *i.e.*, the normal no-load excitation required by a given alternator is 70 volts, and full 80 per cent power-factor load should not require more than 140 volts. Should the excitation voltage be of any other value, *viz.*, 250 volts, the same ratio of excitation holds true.

In designing exciters to meet these conditions the densities of the exciters should be fairly low, especially in the fields. The exciter should also have a time element so that it will be responsive to changes in field excitation to the extent that the voltage will fall, by inserting an external resistance that will equal about three times the resistance of the field, from 125 volts to 25 volts in from six to eight seconds. The ideal exciter designed on these lines will also readily give at full field 165 volts and the increase in field current from 125 volts to 150 volts will not be over 50 per cent. This requirement on the exciter is necessary to take care of the heavy power-load which most central stations are experiencing to-day; and frequently the excitation required on an alternator is 140 volts and in order to obtain the difference between about 100 volts and 140 volts quickly, it becomes necessary that the smaller the increase in field current from 125 volts to 150 volts the quicker the exciter will respond to the short-circuiting of the rheostat, to obtain the desired excitation required by the alternator.

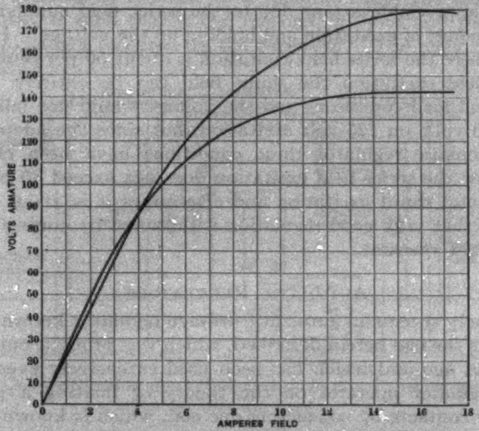


FIG. 1.—Saturation curve of direct-current exciters

Fig. 1 shows a curve giving the saturation on two given exciters, one designed along the aforesaid lines, the other having high saturation with high density and a large increase in shunt field current between 125 and 150 volts. It can be readily seen that the latter exciter is not as suitable for good voltage regulation as the former exciter when an automatic regulator is used.

Before the automatic regulator was perfected the majority of exciters were designed with fairly high densities and very heavy series fields. In some cases the series field equaled 50 per cent of the total excitation of the exciter and with an exciter fully loaded it required a very large amount of resistance in the exciter field rheostat to vary the voltage of the exciter to any appreciable extent due to the series field supplying the large amount of excitation and holding up the voltage. In some cases where the series field excitation is about 50 per cent of the shunt field excitation the shunt field can be entirely broken under full load conditions and the voltage would not fall below 60 to 70 volts on 125-volt excitation, but since the adoption of the automatic regulator these conditions have been changed until now the series field excitation does not exceed 30 per cent of the total shunt excitation and oftentimes it is about 20 per cent, so that very good regulation is obtained by control of the shunt field rheostat.

Automatic Regulators

The only successful automatic voltage regulator known to the author is the one herein described, which was brought out about ten years ago and which has been used extensively ever since. This regulator operates on the theory of floating a pair of primary contacts by connecting one coil, which is known as the direct-current control magnet, to the exciter, bus bar and is graduated by mounting four springs on the lever connected to this control magnet and supported by a pivot at a proper distance so that this lever operates over the 100 per cent range in exciter voltage. These springs are so graduated as to pick up at a difference of 25 per cent in voltage; this keeps a constant torque on the contacts. The alternating-current element of the control magnet, connected to the alternator, is also balanced practically in the same manner except that a counterweight is used instead of springs. It is pivoted in such a manner that with a given voltage—say 110 volts—a balance is produced in which the contacts supported by the alternating-current lever and the contacts supported by the direct-current lever are at an absolute balance, and with the core of the alternating-current magnet arranged to pull in one direction and the core of the direct-current magnet arranged to pull in the opposite direction this balance is produced in such a manner that the main contacts travel less than 1/32 in. (0.8 mm.) to obtain a range of 100 per cent increase in exciter voltage, and the opening at the main contacts in any condition is less than 0.01 in. (0.25 mm.). In addition to the two magnets described above there are also one or more relay magnets, the latter being differentially wound, so that with both windings energized the current is neutralized and the residual is reduced to a minimum and the operation of the relay is such that it can respond, without any time element, to changes required by the generator. The relay magnet is provided with one or more sets of contacts which are connected across the shunt circuit to the exciter field rheostat, the voltage being reduced first to 65 per cent below normal, at which point the rheostat is set before the regulator is cut into service. The alternating-current control magnet is also provided with current winding which is connected to a current transformer in some principal feeder so that the feeder can be overcompounded to take care of the drop in the copper between the central station and center of distribution.

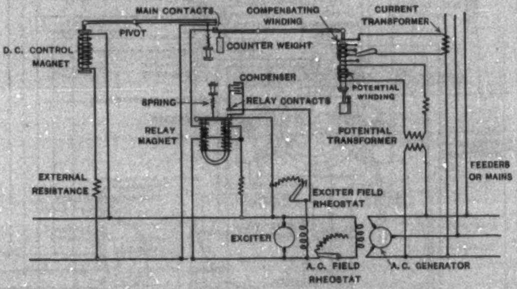

MAIN CONTACTS
COMPENSATING WINDING
CURRENT TRANSFORMER
PIVOT
D.C. CONTROL MAGNET
COUNTER WEIGHT
CONDENSER
SPRING
RELAY CONTACTS
POTENTIAL WINDING
RELAY MAGNET
POTENTIAL TRANSFORMER
FEEDERS OR MAINS
EXTERNAL RESISTANCE
EXCITER FIELD RHEOSTAT
EXCITER
A.C. FIELD RHEOSTAT
A.C. GENERATOR

FIG. 2.—Connections for alternating-current or direct-current generators when exciters are used

An elementary diagram of the small automatic regulator is shown in Fig. 2. This is a small type of voltage regulator now designed for from one to four exciters depending upon their capacity, with as many alternators as it is desired to operate in parallel. For exciters having larger capacity, elementary diagram Fig. 3 shows the same principle of regulator with the exception of the relay magnet which is a magnet designed with circular type flat coils but of the differential design, of which from two to twelve sets of relay contacts are employed, depending upon the size and characteristics of the exciters. The diagram in question shows the connections of two exciters, one set of relay contacts being connected to one exciter while the second exciter has its field rheostat divided up into two equal ohmic divisions having a set of contacts across each division so that the field discharge is taken up by both sets of contacts equally, and this method can be employed with the present design of voltage regulator up to 24 sets of contacts, having two sets of these relay coils in multiple controlled by one set of main contacts.

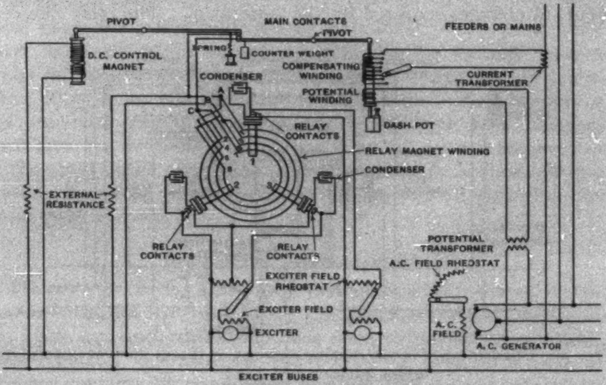

PIVOT
MAIN CONTACTS
PIVOT
FEEDERS OR MAINS
D.C. CONTROL MAGNET
SPRING
COUNTER WEIGHT
COMPENSATING WINDING
CONDENSER
CURRENT TRANSFORMER
A
B
C
POTENTIAL WINDING
DASH POT
RELAY CONTACTS
4
5
6
1
RELAY MAGNET WINDING
CONDENSER
2
3
EXTERNAL RESISTANCE
RELAY CONTACTS
RELAY CONTACTS
POTENTIAL TRANSFORMER
A.C. FIELD RHEOSTAT
EXCITER FIELD RHEOSTAT
EXCITER FIELD
EXCITER
A.C. FIELD
A.C. GENERATOR
EXCITER BUSES

FIG. 3.—Connections of regulator for alternating-current or direct-current generator when exciters are used

REGULATION OF TRANSMISSION LINES

The above regulators are designed to either hold flat bus bar voltage or compensate for non-inductive load through one current transformer. This arrangement does not compensate for an inductive load and in order to accomplish this result a line drop compensator is employed as shown in Fig. 4. Two current transformers are cross-connected in order to deliver the proper amount of current to the line drop compensator which compensator is designed with a reactance coil and resistance coil; the resistance coil being for the non-inductive compensation and the reactance coil being for the inductive compensation. The current coil of the regulator is omitted with this connection and the compensation is secured by the current flowing either through the reactance or resistance coil of the compensator, and can be so adjusted that the voltage can be automatically controlled at the receiving end of a transmission line so that it can be absolutely constant under all conditions of load and power-factor, and will compensate up to 15 per cent above the no-load station voltage.

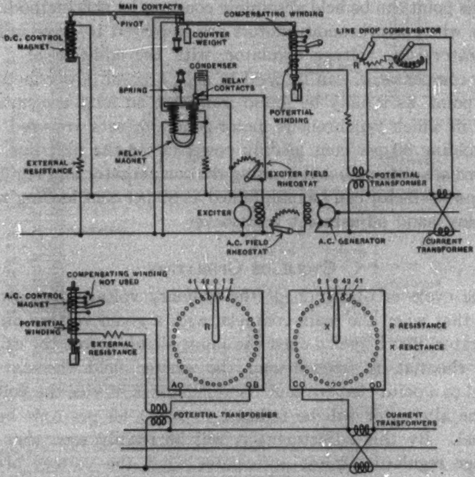

MAIN CONTACTS
PIVOT
D.C. CONTROL MAGNET
COUNTER WEIGHT
COMPENSATING WINDING
LINE DROP COMPENSATOR
R
X
CONDENSER
SPRING
RELAY CONTACTS
POTENTIAL WINDING
RELAY MAGNET
EXTERNAL RESISTANCE
EXCITER FIELD RHEOSTAT
POTENTIAL TRANSFORMER
EXCITER
A.C. FIELD RHEOSTAT
A.C. GENERATOR
CURRENT TRANSFORMER
COMPENSATING WINDING NOT USED
A.C. CONTROL MAGNET
POTENTIAL WINDING
EXTERNAL RESISTANCE
41 42 0 1 2
R
A
B
2 1 0 42 41
X
C
D
R RESISTANCE
X REACTANCE
POTENTIAL TRANSFORMER
CURRENT TRANSFORMERS

Fig. 4.—Connections of regulator for alternating-current generator using line drop compensator

On long transmission lines where a large drop in voltage is experienced from heavy inductive loads it is generally conceded that the adoption of synchronous condensers is an advantage in increasing the output of the central station, and by the application of an automatic voltage regulator with a condenser of the proper size the installation can be made in some remote place along the line where the condenser or regulator need very little attention and the condensers can be used for automatically compensating for line drop.

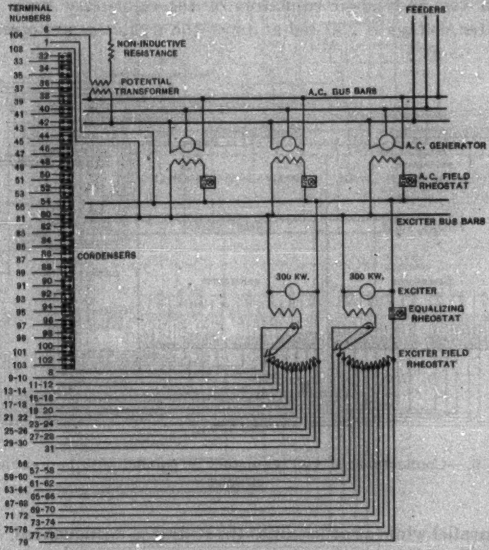
The same connections as employed in the alternating-current generator is applicable to synchronous condensers. The operation of the regulator is such that when the voltage tends to fall at the motor terminals due to heavy inductive load, the regulator will increase the excitation on the condenser and tend to deliver leading current to the line until this voltage is restored to normal, and as aforesaid, with the proper size of condenser the regulation at this point can be held absolutely constant by this method. In cases where synchronous motors are employed to drive railway generators the voltage regulator, with the addition of a line drop compensator, can be used to hold a given power-factor at this point, as it may be found from test on long transmission lines in which synchronous motor-generator sets are used that by holding 80 per cent leading power-factor the best line conditions are obtained, and in using the compensator and regulator this power-factor can be maintained at 80 per cent leading without any hand adjustment whatsoever.

Cycle of Operation

The cycle of operation of the ordinary voltage regulator is such that when the main contacts, with a given voltage on the generator, just begin to open the shunt circuit across the exciter field rheostat is opened and the exciter field rheostat reduced to a point that without the regulator in service the voltage on the alternator will be reduced to about 65 per cent below normal. By this adjustment it will be readily seen that the voltage regulator almost anticipates when the voltage of the alternator is about to change. Therefore by the adoption of the floating-contact system this regulator does not wait until the voltage actually changes before it operates, but it is continually operating due to the large percentage of resistance turned into the exciter field circuit; while with regulators of types which at a given voltage are stationary it requires change in voltage until these regulators operate in either one direction or the other. It can be readily seen that such a type of regulator would be unsatisfactory due to the time element in the regulator itself. This is primarily the reason why the present type of automatic voltage regulator has been so successful, as the regulator does not have to wait for the voltage to change but is operating all the time owing to the fact that the voltage is tending to drop, but the regulator operating at a higher rate of vibration and intermittently short-circuiting and opening the shunt circuit across the exciter field rheostat makes the time element negligible.

INSTALLATIONS OF VOLTAGE REGULATOR

Connecticut River Power Co. As a practical illustration of the generator capacity for which the automatic voltage regulator is now employed the plant of the Connecticut River Power Company may be cited, in which alternating-current generators aggregating 20,000 kw. are equipped with these regulators. The two 300-kw. 125-volt exciters are driven from vertical turbines and operate in parallel on one voltage regulator. The connections of this regulator are shown in Fig. 5, in which it will be noted that the 12 set of contacts are connected to each exciter


TERMINAL NUMBERS
6
104
1
105
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
60
61
62
63
64
65
66
67
68
69
90
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92
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99
100
101
102
103
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9-10
11-12
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15-16
17-18
19-20
21-22
23-24
25-26
27-28
29-30
31
56
57-58
59-60
61-62
63-64
65-66
67-68
69-70
71-72
73-74
75-76
77-78
79
NON-INDUCTIVE RESISTANCE
POTENTIAL TRANSFORMER
CONDENSERS
FEEDERS
A.C. BUS BARS
A.C. GENERATOR
A.C. FIELD RHEOSTAT
EXCITER BUS BARS
300 KW.
300 KW.
EXCITER
EQUALIZING RHEOSTAT
EXCITER FIELD RHEOSTAT

FIG. 5.—External connections of regulator with two exciters in parallel.

field rheostat. The rheostats are divided into 12 ohmic divisions, and it is impossible to see the slightest arc at the relay contacts. A line-drop compensator is also employed in this plant to compensate for the large inductive drop in the transmission line and the voltage is controlled automatically at the receiving end of the 66,000-volt, 60-mile (96.5 km.) transmission line.

Ontario Power Co. Another application of the automatic regulator is in the plant of the Ontario Power Company which delivers 30,000 kw. and contains two 375-kw. exciters equipped with two individual regulators of the eight-relay type. The exciter voltage is 250 and at times the regulators are operating

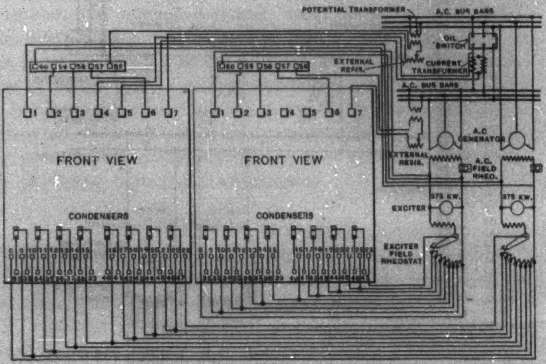
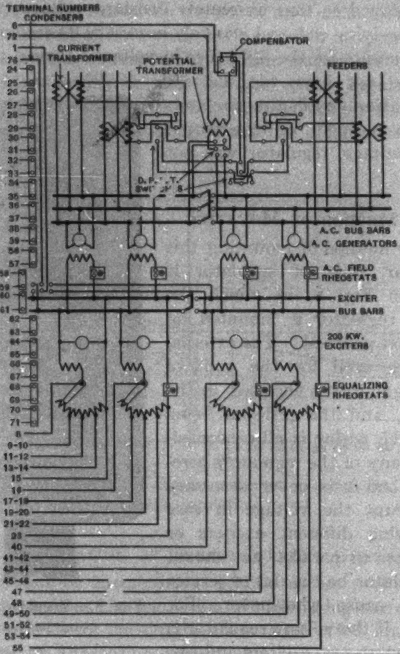

POTENTIAL TRANSFORMER
A.C. BUS BARS
OIL SWITCH
EXTERNAL RESIS.
CURRENT TRANSFORMER
A.C. BUS BARS
60
59
58
57
56
1
2
3
4
5
6
7
FRONT VIEW
FRONT VIEW
A.C GENERATOR
EXTERNAL RESIS.
A.C. FIELD RHEO.
375 KW.
375 KW.
EXCITER
CONDENSERS
CONDENSERS
EXCITER FIELD RHEOSTAT

Fig. 6.—Connections of two regulators in parallel with two exciters in parallel

in parallel while at other times the station is sectionalized, each regulator being employed to control the voltage of one side of the station. When the regulators are operating in parallel it is necessary to install either a line-drop compensator between the regulators or to install a current transformer out of phase with the potential transformer as shown in Fig. 6, so that the cross currents which are liable to be produced by the two regulators operating in parallel can be overcome. When the stations are operating in parallel with a regulator in each station the reactance is usually sufficient so that the cross currents are not produced by the regulators, but on short transmission lines trouble from cross currents with two generators operating in parallel with two regulators is liable to be encountered unless either of the above methods is used with one or the other of the regulators.

To further illustrate the flexibility of the large capacity voltage


TERMINAL NUMBERS
CONDENSERS
CURRENT TRANSFORMER
POTENTIAL TRANSFORMER
COMPENSATOR
FEEDERS
D.P.D.T. SWITCHES
A.C. BUS BARS
A.C. GENERATORS
A.C. FIELD RHEOSTATS
EXCITER BUS BARS
200 KW. EXCITERS
EQUALIZING RHEOSTATS
6
72
1
76
24
25
26
27
28
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30
31
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37
38
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49-50
51-52
53-54
55

FIG. 7.—External connections of regulator for arrangement of four exciters

regulator, Fig. 7 shows a 16-relay regulator arranged for controlling four 8000-kw. alternators receiving excitation from four 200-kw. exciters. It will be noticed that the alternating-current as well as the direct-current bus bars are arranged for sectionalizing, so that the station can be operated with the regulator on either set of busses, and a line-drop compensator is supplied so that it will control any one of four feeders. If the total station is operating in parallel and the regulator is controlling the principal feeder for compensation of line drop, the voltages on the remaining feeders at the center of distribution will agree very closely, but if the feeders are of variable lengths feeder regulators are employed so that absolutely constant voltage can be held at the receiving end, and it is only necessary for feeder regulators to compensate for the difference in voltage between the feeders. They do not have to take into consideration any fluctuating voltage such as might be experienced if the voltage regulator was not used.

NEW METHOD OF MOUNTING

A new method of mounting this particular type of regulator is shown in Fig. 8, in which the voltage regulator is mounted on a cast iron pedestal. The external resistance used for the coils of these regulators is enclosed in the pedestal, and the pedestal being hollow the wiring is all concealed.

With any of the regulators herein described it is never necessary to interrupt the voltage in case of throwing different exciters or alternators in parallel, nor should the regulator be cut out of service for any cause whatsoever. For example, if the voltage regulator is connected to two exciters and two alternators and the load becomes such that it is necessary to start up the third alternator and exciter; the exciter is first brought up to the proper voltage and paralleled; the voltage regulator is then connected to the third exciter; the resistance turned into the exciter field to a point that will reduce it to 65 per cent below normal, and the load between the exciters is equalized by a small resistance placed in series with the exciter which tends to take the greater portion of the load when both the exciter field rheo-

FIG. 8.—Regulator mounted on pedestal

stats are short circuited by the regulator. The alternator is then synchronized and placed in parallel and no interruption in service is occasioned. Should it be necessary to take out one alternator and exciter it is first desirable to transfer the load from the generator which it is desired to shut down. The main switches on the generator are then tripped out and the load is transferred from the exciter by the use of an equalizing rheostat in the same manner and the main exciter switch is opened, after which the contacts corresponding to this exciter are cut out. It will therefore readily be seen that the voltage regulator can be employed 24 hours a day without any interruption whatsoever from either paralleling or cutting in and out different machines or feeders.

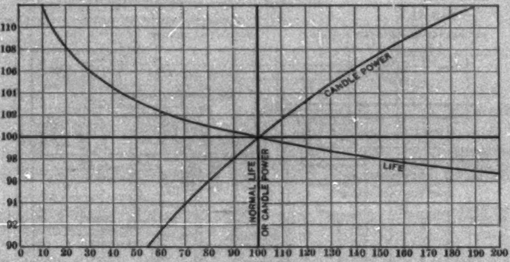

FIG. 9.—Relation of light and candle power of incandescent lamps to voltage regulation

VOLTAGE REGULATION OF DIRECT-CURRENT GENERATORS

The regulation of direct-current generators has probably not been as important as the regulation of alternating-current generators because direct current has been superseded for central station work by alternating-current, due to a number of well-known reasons. For isolated work, such as office building, apartment houses, and hotels, with the present practice of installing elevators and lights on the same circuit, is necessary to have some means of automatic regulation for the direct-current generator. A large variation in voltage due to starting the elevators will be experienced and cause a loss in the candle-power of the lamps which not only decreases their brilliancy but shortens their life to a considerable extent. To briefly show the variation in life and candle-power of an incandescent lamp which is subject to voltage variation the curves of Fig. 9 are given, showing that if the voltage drops 2 per cent it reduces the candle-power of the lamp to 89 per cent of normal, and a 2 per cent increase in voltage reduces the life to 65 per cent of normal. It can readily be seen that the more closely the voltage is maintained the longer will be the life of the lamp. This holds true with alternating-current lighting as well as direct-current lighting.

The principle of regulation of the direct-current generator is shown in Fig. 10. The voltage regulator is designed with one main control magnet which is connected permanently to the bus bars of the direct-current generators, and has one movable and one stationary core. These cores at a given flux are balanced by the spring, calibrated so as to float them at a certain voltage. The lever supporting the core and spring is equipped with a pair of contacts which operates a relay. For simplicity this relay is shown series wound. The main contacts open and close the winding of the relay which overpowers the spring supporting the armature which carries the relay contacts. The relay contacts are connected across the shunt field rheostat, which is first turned to give about 35 per cent of the normal voltage which it is desired to maintain, so that when the relay contacts are closed the generator voltage tends to rise until it reaches normal value. The main contacts are opened which in turn open the relay contacts which tends to reduce the voltage 35 per cent below normal, but this does not actually happen as the main contacts being set for a given voltage and operating

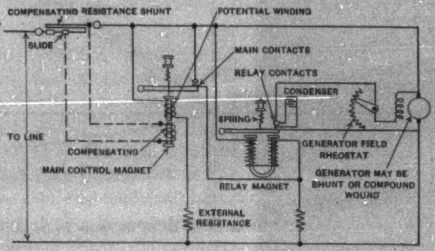
COMPENSATING RESISTANCE SHUNT
POTENTIAL WINDING
SLIDE
MAIN CONTACTS
RELAY CONTACTS
CONDENSER
SPRING
TO LINE
COMPENSATING
MAIN CONTROL MAGNET
GENERATOR FIELD RHEOSTAT
GENERATOR MAY BE SHUNT OR COMPOUND WOUND
RELAY MAGNET
EXTERNAL RESISTANCE

FIG. 10.—Connections of regulator for direct-current generator

at a very high rate of vibration the voltage is maintained at the predetermined value and is constant under all conditions of load and speed changes. This was one of the first successful voltage regulators for direct-current generators but it was limited in capacity to one relay. As most direct-current generator installations require two or more generators of from 100 to 200 kw. capacity each, a single-relay regulator was found to be too small to handle the field discharge of these large generators. It was therefore necessary to resort to the multiple relay type of regulator which operates on the same principles but which has a number of relays controlled by one set of main contacts. The multiple relay type of direct-current regulator differs slightly from the alternating-current regulator in the design of the relays which are differentially wound with parallel conductors so as to neutralize the self-induction of the coils thus eliminating the sparking at the main contacts. It is impossible to place a condenser section across the main contacts owing to the condenser discharge causing the main contacts to stick, the break not being sufficient to allow the condenser to discharge properly; and if the break is large enough to allow this discharge the regulation will be affected. Condensers are placed across the relay contacts to absorb the arc as these contacts are usually set

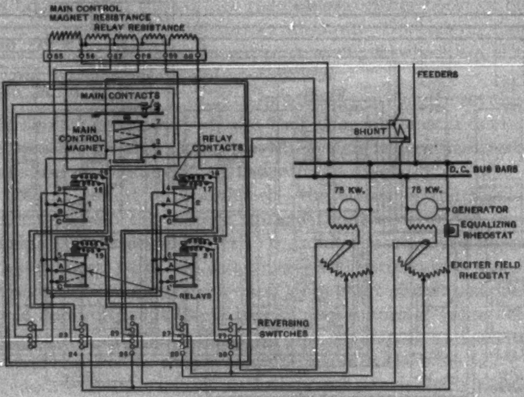
MAIN CONTROL
MAGNET RESISTANCE
RELAY RESISTANCE
FEEDERS
MAIN CONTACTS
MAIN CONTROL MAGNET
RELAY CONTACTS
SHUNT
D.C. BUS BARS
75 KW.
75 KW.
GENERATOR
EQUALIZING RHEOSTAT
EXCITER FIELD RHEOSTAT
RELAYS
REVERSING SWITCHES

FIG. 11.—Connection of regulator for two direct current generators in parallel

about 1/32 in. (0.8 mm.) apart. The connections to the generator field rheostat when multiple relays are used are shown in Fig. 11, in which it will be noted that there are four relays in multiple operating with one set of main contacts. They are operating on two 75-kw. generators having the resistance of each generator divided into two equal ohmic divisions. For the compensation of line drop a shunt is used in the principal lighting feeder which is connected to the current winding of the main control magnet which opposes the potential winding. As the current increases in the shunt the potential winding is opposed by the current winding and the spring overpowers the core and raises the voltage so that it is possible to compensate about 15 per cent drop in feeder circuits. Another method of regulating direct-current generators is to employ the alternating type of floating contact regulator and separately excite the direct-current generators from an exciter. The direct-current generator in this case virtually becomes an alternating type of generator as far as the principle of regulation is concerned. For Edison three-wire systems, two regulators and two exciters are employed as shown in Fig. 12. For large direct-current installations the latter arrangement is very satisfactory as the

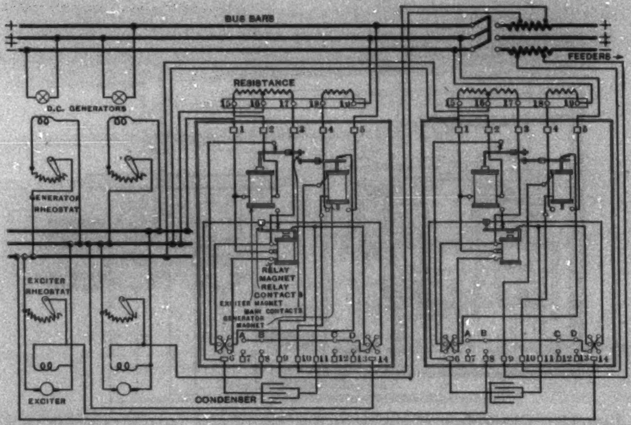
BUS BARS
+
±
−
+
±
−
FEEDERS
RESISTANCE
15
16
17
18
19
1
2
3
4
5
D.C. GENERATORS
GENERATOR RHEOSTAT
EXCITER RHEOSTAT
RELAY MAGNET
RELAY CONTACTS
EXCITER MAGNET
MAIN CONTACTS
GENERATOR MAGNET
A
B
C
D
6
7
8
9
10
11
12
13
14
CONDENSER
EXCITER

FIG. 12.—Two regulators on a three-wire direct-current system using exciters

current to be handled by the regulators is very small and they can also be arranged for overcompounding for line drop by the shunt described above—the current winding opposing the potential winding of each regulator. The exciters for the main generators operate in series the same as the generators themselves.

SPECIAL REGULATORS

There are numerous applications of voltage regulators which no attempt will be made to describe in this paper, such as regulating alternating-current systems where a storage battery is floating on the exciter bus. The method employed here is to use a booster with the voltage regulator to either boost or buck the exciter voltage to the proper amount. Special regulators are also in use for constant-current work, flywheel equalizing sets, and many other special applications.

There is one special appliance in addition to voltage regulators which should be mentioned, and that is an automatic device to be placed on an alternating-current system where heavy short circuits are encountered. If the voltage regulator is employed and a short circuit is experienced—the action of the regulator will tend to hold the voltage up and therefore give the exciter full field. Often in hydroelectric installations when this happens the water wheel gates are wide open—full excitation is supplied to the exciters and generators—and if the short circuit is suddenly relieved the voltage is likely to rise above normal value before the excitation can be reduced on the generators and exciters. The time required to reduce this excitation is the time taken by the generators and exciters to demagnetize their fields between maximum full field voltage and the voltage corresponding to the normal load excitation, which may be from two to six seconds. This is augmented by the time required for the water wheels to reduce the speed to normal. This can be overcome by placing overload and high-voltage relays in the transmission lines set so that should the current increase to a given value the relays will trip, open the connections to the regulator and reduce the voltage to a certain value (to be determined by the operating engineer) and after the short circuit is burned off and the current become normal again the relays will close and the regulator will automatically be returned to service.

While the above device is not necessary in ordinary central stations it is a very important factor in large hydroelectric installations.

DISCUSSION ON "VOLTAGE REGULATION OF GENERATORS", SCHENECTADY, FEBRUARY 16, 1911.

H. G. Reist: I would recommend this paper to the careful consideration of engineers who design and operate stations, and call attention to the fact that the use of regulators in stations allows us to build generators having inherent regulation not as good as has been thought desirable in the past. The reason for desiring generators having poorer regulation was fully discussed this morning but I might repeat that it is desirable to have such machines to avoid excessive currents and thus endanger generators and other station apparatus in case of a short-circuit on the system. Reducing the flow of currents during short-circuits is of advantage in every respect except that it spoils the regulation of the system. In large systems this is usually of no importance and in small ones the potential can readily be maintained by means of regulators.

Carl J. Fechheimer: That poor regulation rather than close regulation of alternators is really desirable in a great many cases is becoming more and more the opinion of engineers. This applies especially to high-speed generators, particularly those of the turbo type, in which the size of machine is almost entirely determined by rotor heating and stresses, it being understood that these generators supply current for induction motors, so that the load of the system is inductive and the power factor rather low.

It is usually considered to be essential at the present time for generators to maintain their voltage at 25 per cent overload, 80 per cent power factor. It may be shown that the ratio of the maximum ampere turns in the field winding to the ampere turns in the stator at full load is nearly fixed for a definite regulation and for the amount of overload which the generator should carry at the power factor of the circuit, and still maintain its voltage. From this it will be seen that if the voltage regulation be very close it results in a rather large rotor or else great heating in the rotor; hence, from this point of view we can materially gain if we sacrifice regulation slightly, a voltage regulator being used.

As the size of units and transmission systems increase in their output, close voltage regulation is often found to be unnecessary, as the changes in load on the system are very slight compared with the combined output of the units supplying power to the system. In such cases the change in voltage is hardly sufficient to detect a perceptible change in the illumination produced by the lights on the circuits.

From another viewpoint, close voltage regulation would be undesirable as this also implies that in case of short circuit the damage which may be done to the end connections of the generators and to other apparatus may be considerable.

There is, however, one serious objection to having poor inherent regulation when a regulator is used and that is, if the currents of the various phases of the generator be unbalanced, the voltages will be correspondingly unbalanced, with the result that the lights will burn dimly on one phase and brightly on another. While this may be remedied with the use of compensators, it is only done by complications which would be unnecessary were the generator to have closer regulation.

It is my opinion that reasonably good regulation is very desirable in small generators (up to 500 kilovolt-amperes) and that it becomes of less importance as the size of the generator is increased. In a 5000-kilovolt-ampere alternator, a regulation of 15 per cent at 100 per cent power factor and 30 per cent at 80 per cent power factor should be sufficiently close for nearly all cases.

E. F. Alexanderson: The Tirrill regulator is usually thought of as a voltage regulator, but I wish to call attention to the varied possibilities for its application. Ordinarily the regulator is adjusted so as to maintain constancy of a certain electric quantity, for instance, voltage, current, or combination of the two. This is done by balancing the attraction of the regulating magnet against a counter weight or spring pressure. In many cases, however, it is desired not to maintain the constancy of the voltage or current, but to regulate the relative magnitude of two electrical quantities, for instance, to regulate the relation of wattless current to energy current; in other words, automatic regulation of the power factor by a synchronous machine, or maintaining equality of the two voltages in a three wire system by a balancer set. In such a case the regulating magnet is not balanced against a spring, but equilibrium is established by the equal and opposite attraction of two magnets, or by the action between two magnets becoming zero due to the currents being out of phase.

There are numerous variations of this principle, and, in general, it is only worth while remembering that the regulator is an instrument which lends itself with only slight or no modification to the automatic regulation of almost any electrical quantity that can be measured.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

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THE DIRECTION OF ROTATION IN ALTERNATING-CURRENT VECTOR DIAGRAMS

BY ERNST J. BERG

The object of this brief is to present the writer's views on the proper vector representation of alternating-current phenomena. The question is attacked from the point of view of the teacher of alternating currents to undergraduate students.

In electrical engineering are treated chiefly the phenomena which are caused by alternating currents and e.m.fs. The currents as well as the e.m.fs. are periodic functions of time; as the time changes, the instantaneous values of these functions also change. Thus, it seems rational to consider time as the independent variable in illustrating such phenomena.

In representing them graphically, several methods are conceivable, but it seems to the writer that the following two are simplest and indeed the only two which by their simplicity can be considered when dealing, as is always done in practice, with phenomena involving multiphase work and more especially multiphase work with distorted waves.

It is realized that in the case of single-phase circuits with sine waves of current and e.m.fs. other methods may seem as simple, and by many, simpler.

First. Rectangular coördinate system with time as abscissas and instantaneous values of current and e.m.f. as ordinates.

This is illustrated in Fig. 1, which gives the changes in current in a three-phase system.

Second. Polar coördinate system. In this case the independent variable—the time in represented by the angle ϕ, and the instantaneous values of the currents by the radii vectors. The result in case of a sine wave is the polar curve, the circle.

Thus, in a symmetrical three-phase system, the values of the currents in the three lines is found by reference to the three circles in Fig. 2.

In this particular diagram, zero time is represented by the position of vector *O A*.

The values of the currents in the three lines at that time are expressed by:

In line *I+O A*.
In line *II—O B*.
In line *III—O B*.

It is at once evident to the student that the current that flows out over line *I* is returned partly by line *II*, and partly by line *III*. In this case, one-half of the current returns over line *II*, the other over line *III*.

The student sees that it is the *same current*; sees that the three instantaneous currents are in phase.

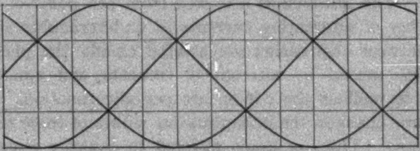

FIG. 1

The currents at time ϕ are:

In line *I+O C*.
In line *II O*.
In line *III—O D*.

The student sees that at that particular time, line *II* carries no current; all current that leaves line *I*, returns in line *III*. He sees that in a four-wire three-phase system with balanced load, there is no current in the neutral line, all current going out in one line returns in one or both of the other main lines.

The diagram, if referred to the e.m.fs. instead of currents, shows that the common connection is at neutral potential since at all instances the positive voltage is as great as the negative.

In the case of distorted waves, and all waves in actual engineering are distorted, the diagram lends itself with equal facility. In Fig. 3 is given the counter e.m.f. of a transformer corresponding to a sine wave of exciting current, a wave approximately obtained between one of the lines and the neutral of Y-connected transformers in the three-phase system.

This wave contains a large triple frequency component and some components of higher frequency.

The instantaneous values of the three currents at any one time is obtained as readily as in the first case. It is seen here that the common connection has not neutral voltage. Thus, there is an active e.m.f. generated between the " neutral " and the three lines as returns.

With such distorted wave, a considerable current would flow to the common connection, if such were established, even if the three-phase load was balanced.

It is readily shown that any other odd harmonics except the third and its multiples do not cause a pulsating voltage between the neutral and the outside lines, the algebraic sum of the three e.m.fs. are at all lines zero. This is illustrated in Fig. 4 which shows the distorted wave of the fundamental and a fifth harmonic of one-half the intensity of that of the fundamental.

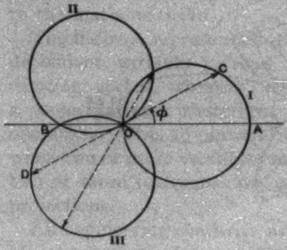

FIG. 2

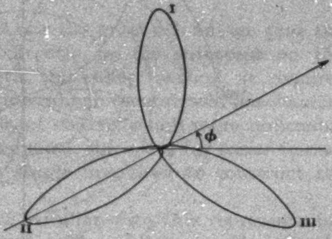

FIG. 3

The polar coördinate system has also another great advantage in determination of the effective values of a distorted wave. It is well known that the square of the effective value is obtained by dividing the area as obtained by planimeter by $\frac{\pi}{2}$.

In teaching alternating current phenomena, it is in the writer's opinion absolutely necessary to dwell a long time on the instantaneous variations. His experience is that by this method and this method only can the student get a clear insight of the theory. It seems nearly useless to teach electrical engineering by referring at once to vectors of effective currents and e.m.fs. only. These should be introduced first after the students have obtained thorough knowledge of the instantaneous changes.

The writer is frank to confess that he has failed to see a simple application of the so-called crank diagram in these cases.

The crank diagram, to be sure, lends itself readily to simple single-phase diagrams with sine wave of currents and e.m.fs.; that is, to circuits and conditions which are not found in practice, it lends itself only to very expert mathematicians in case of multiple phase circuits with distorted wave shapes.

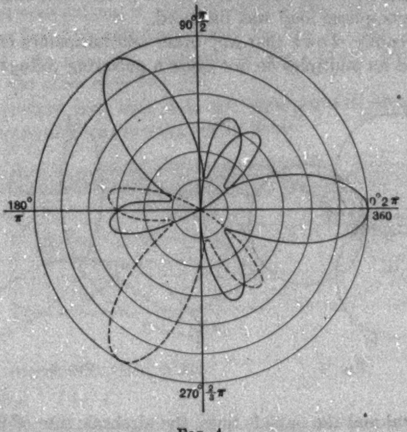

FIG. 4

It seems unlikely that sufficient time can be found in undergraduate work to explain the necessary mathematics. It seems also that the diagrams become so complex as to be almost beyond interpretation.

If it is agreed that the polar-coördinate system with time as independent variable, is preferable, then the whole controversy seems to me settled. It is not a question of direction of rotation; the rotation is counter clockwise in any case. In the polar coördinate system, time rotates counter clockwise. In the crank diagram the e.m.fs. or currents are made to rotate counter clockwise.

The adoption of the polar diagram settles the complex expression of current, impedance, etc.

$I = i + j\, i_1$ represents a lagging current

$r - j\, x$ represents an impedance.

To sum up, it is the writer's opinion that the indirect representation, the polar circle diagram, Steinmetz' method, or whatever the representation is called by various writers, is preferable to the so-called direct representation, or the crank diagram, for the following reasons:

It is a simple application of polar coördinates, whereas the "direct representation" is a mixture of the polar and the rectangular coördinate systems, a system which hardly appeals to the mathematician.

The indirect representation has the great advantage that the dependent variable is read directly as the intercept on the rotating vector, whereas, with the other method, it requires a projection and, therefore, an added mental and mechanical operation. This advantage is, of course, much more noticeable when two or more variables are used, since it is far easier to read two or more intercepts on a single line than to construct the projections.

All engineering students are familiar with this representation of interception of a rotating line from their work with the Zeuner diagrams so that it is at once understood by them.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

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CONVENTIONS IN CLOCK-DIAGRAM REPRESENTATION

BY W. S. FRANKLIN

Everyone understands the vector representation of simple alternating electromotive forces and currents, and therefore a skeleton outline will be sufficient to call to mind the connection between: (*a*) the two styles of clock-diagram, and (*b*) the usual geometrical conventions in trigonometry and the usual conventions governing the geometrical interpretations of complex quantity in algebraic analysis.

Definition. A harmonic electromotive force (or current) is an electromotive force (or current) which varies as the sine or cosine of an uniformly increasing angle. This may be expressed in accepted notation by the familiar equation:

$$e = E \sin \omega t \tag{1}$$

In the geometric representation of harmonic electromotive forces and currents two styles of clock-diagram are in use. These we will designate as *diagram A*, and *diagram B*.

CONCERNING DIAGRAM *A*

1. The customary representation of a positive angle θ is shown in Fig. 1.

2. The customary representation of $\sin \theta$ and $\cos \theta$ is shown in Fig. 2.

3. The customary representation of a uniformly increasing angle is shown in Fig. 3.

4. The representation of a harmonic electromotive force in conformity with Figs. 1, 2 and 3 is shown in Fig. 4.

5. The representation of a lagging current in conformity with Fig. 4 is shown in Fig. 5.

6. In Fig. 5 the leading vector *E* is the leading quantity in time phase.

7. *The Addition Theorem.* The most important thing in the vector representation of harmonic electromotive forces (or currents) is what may be called the addition theorem. Stated in purely geometrical terms this theorem is that the sum of the projections of the two sides of a parallelogram is equal to the projection of the diagonal. A simple example of the addition theorem is shown in Fig. 6.

NOTE:—All diagrams show positive values according to established conventions.

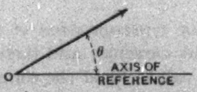

FIG. 1

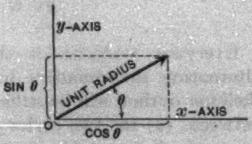

FIG. 2

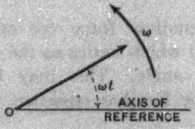

FIG. 3

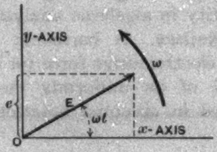

FIG. 4

CONCERNING DIAGRAM *B*

8. The customary representation of polar coördinates *r* and θ is shown in Fig. 7.

9. The polar-coördinate representation of a harmonic electromotive force $e = E \sin \omega t$ is shown in Fig. 8. For the sake of visualizing the function *e*, it is represented in Fig. 8 as the projection of a fixed *E*-vector upon the rotating radius vector. In this way it has come about that the fixed *E*-vector in Fig. 8 is thought of as representing the given harmonic electromotive force in substantially the same way that the rotating *E*-vector in Fig. 4 represents a given harmonic electromotive force.

10. The representation of a lagging current in conformity with Fig. 8 is shown in Fig. 9.

11. In Fig. 9 the leading vector in space is the lagging quantity in time phase.

12. *The Addition Theorem.* Those who prefer clock-diagram *B* seem to emphasize the polar-coördinate idea and to minimize the projection idea. A certain loss of simplicity is involved in this emphasis as may be shown most strikingly by stating the all-important addition theorem in terms of circular loci: The sum of the portions of the radius vector which are cut off by two given circles passing through the polar origin is equal to the portion of the radius vector which is cut off by a third circle whose diameter is the diagonal of the parallelogram constructed on the diameters of the given circles as sides.

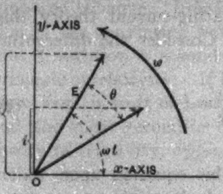
y-AXIS
ω
E
θ
e
I
i
ωt
x-AXIS
O

FIG. 5

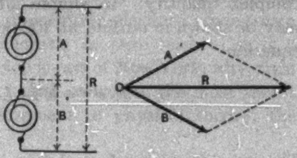

FIG. 6

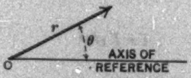
r
θ
AXIS OF REFERENCE
O

FIG. 7

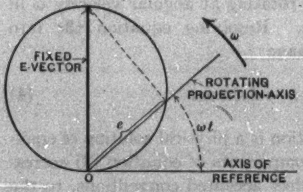
FIXED E-VECTOR
ω
ROTATING PROJECTION-AXIS
e
ωt
AXIS OF REFERENCE
O

FIG. 8

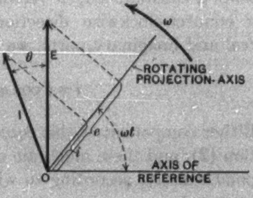
ω
θ
E
ROTATING PROJECTION-AXIS
I
e
i
ωt
AXIS OF REFERENCE
O

FIG. 9

IMPORTANCE OF THE IDEA OF PROJECTION

There is no question as to the fundamental importance and simplicity of the idea of projection in the representation of the sine and cosine in trigonometry, and the importance and simplicity of the idea of projection in the representation of any sine or cosine function is equally beyond question.

If the idea of projection is to be used in the most powerful way, the projection axis must be looked upon in a sense as a reference axis and it should be stationary; at least this is the conventional point of view in nearly every case in which sine or cosine functions are used in geometry or physics.

The idea of projection on fixed axis of reference is the basis of the conventional geometrical and physical interpretation of complex quantity. In simple alternating-current theory this may be shown in outline as follows: Consider the differential equation

$$E\,\epsilon^{j\omega t} = R\,i + L\,\frac{d\,i}{d\,t} \tag{2}$$

The important singular solution of this equation upon which the whole of the elementary theory of alternating currents is based is:

$$i = I\,\epsilon^{j\omega t} \tag{3}$$

Now according to established conventions this equation represents a constant-length vector rotating at angular velocity ω in a counter-clockwise direction. Resolving equation (**3**) into real and imaginary parts, we have

$$i = I \cos \omega\,t + i\,I \sin \omega\,t \tag{4}$$

Either component of this equation is a physical solution of equation (**2**), and these algebraic components of equation (**3**) correspond exactly, according to widely accepted conventions, to the geometric components of the rotating I-vector in a clock diagram like Fig. 4.

THE DIFFERENCE BETWEEN DIAGRAMS *A* AND *B*

Let us call diagram *A* with all of its accompanying ideas and conventions a *group*, and likewise diagram *B*. Now if the difference between two such groups depends upon one item, then this difference can be expressed in as many ways as corresponding items of groups *A* and *B* can be combined. Such is the *group theory* explanation of this and of most other long-drawn-out and inconsequential discussions among men. Thus may the most recent and the most recondite development of pure mathematics be *applied!*

The fact is that diagram *B* differs from diagram *A* in that diagram *B* does violence to the established convention as to the positive direction of rotation. This is a fact. Unfortunately it can be stated in a great variety of ways, but it is a fact. Some may object, for, behold! the direction of rotation in Figs. 4 and 8 is the same! To such we declare, again, the fact, as above stated. It is a question of what moves, or, rather, of what is supposed to move. Indeed (and it is with a profound appreciation of the convincing power of scientific elegance among men that I mention a second modernism in pure science) it is a principle of relativity. If London is east of New York, why, then New York is west of London. And so we see the most recent and the most recondite development of physical theory, the theory of relativity, *applied!*

DISCUSSION ON "THE DIRECTION OF ROTATION IN ALTERNATING CURRENT VECTOR DIAGRAMS", "CONVENTIONS IN CLOCK-DIAGRAM REPRESENTATION." SCHENECTADY, FEBRUARY 16, 1911.

G. L. Hoxie (by letter): Mr. Berg's paper presents very clearly certain undoubtedly valuable features of the polar-diagram-representation of alternating quantities. This kind of diagram has been made familiar to us in this country mainly by the joint writings of Messrs. Berg and Steinmetz. It seems to me, however, that the question is not so much that of selecting a "proper" method of graphical representation, to the exclusion of other methods, as a question of selecting for a given case the method best adapted to it.

In the teaching of alternating currents to undergraduates, it has been my experience that some students will pick up an idea in one way and some in another, and that the teacher should present the same matter from as many angles as possible, and with almost endless repetitions. It would seem that the majority of students find the rectangular coördinate system most readily grasped. A few others will find that the polar system, illustrated in Figs. 2, 3 and 4, seems simpler. There will also be some students who will understand the rectangular diagram (Fig. 1), first, and thereby be helped to grasp the meaning of the polar diagram, which latter they will thereafter prefer.

All of this however has to do with the *explaining* or *describing*, of phenomena. As Mr. Berg very truly says, the teacher must dwell a long time on instantaneous variations, and the student gets his first clear understanding from the rectangular and polar systems described in the paper. The idea of rotating and projecting a vector, particularly when the length of the vector is not constant, is unquestionably more difficult.

After the student has been thoroughly grounded on the general features of the alternating circuit, so that he understands pretty well what we mean when we speak of leading and lagging currents, how currents combine in three phase circuits, and in various unbalanced circuits; or in short when he has a good general *qualitative* knowledge, it is necessary to introduce him to some tools to use in solving problems. From this point I believe the rectangular and polar diagrams should mainly be dropped, being occasionally introduced in connection with some particular problem to refresh the comprehension of instantaneous conditions.

The notion of vectors, the idea of projection, and the complex quantity, should be explained. The analytical and graphical conventions of the complex quantity should be learned, and the effective values of currents and electromotive forces (considered thereafter rather arbitrarily as directed quantities), should then mainly be dealt with. Usually, at first, solutions should be graphical, carefully making diagrams to scale—and later on analytical, making use of the complex quantity. The conventions that were used some years ago by Dr. Kennelly, in an Institute paper dealing with hyperbolic functions, seem to me the best ones to follow.

I entirely agree with Mr. Berg as to the desirability of cutting out complex mathematics. If any mathematics looks complex to Mr. Berg, it is not likely that many Institute members will care to spend much time on it.

Charles P. Steinmetz (by letter): It is regrettable that two different representations of alternating vectors exist, of which the one appears like the mirror image of the other. The difficulty extends to the symbolic representation of the vectors, as in the one, the time diagram, inductive impedance is represented by $Z = r - j\,x$, and in the other, the crank diagram, by $Z = r + j\,x$.

It would be very desirable to reach an agreement on vector notation, but this does not seem feasible, due to the apparent impossibility of getting an intelligent decision on the subject, as many of the men who discuss the subject and write on it, are familiar with one representation only, but never have taken the trouble to understand the other representation, but, since it appears like the image of the notation familiar to them, merely assume it to be rotation in opposite direction. All the briefs written on the matter do not appear to change the condition, since they do not seem to be read. It appears hardly fair and reasonable to accept the judgment of somebody, who has not taken the trouble to understand the subject, on which he judges.

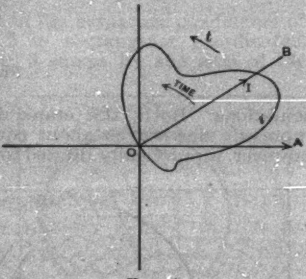

FIG. 1

To some extent, an illustration hereof is the title of the Institute discussion " On Vector Rotation ", though it is not a question of rotation at all, as both methods rotate in the same direction, counter-clockwise, but a question of *notation*, that is, of the meaning of the vector.

If the difference in the two representations were merely the difference in the direction of rotation, the symbolic representation would be the same: since $+j$ mathematically represents an angle 90 degrees behind $+1$, $+j$ in the crank diagram represents a vector, which has moved 90 degrees farther, that is, is ahead in rotation, or leading the vector $+1$, regardless whether the direction of rotation is counter-clockwise or clockwise, and in the time diagram, $+j$ represents a vector of a phase, which is 90 degrees later in time, than $+1$, that is, lags by 90 degrees, regardless again, whether the rotation is clockwise or counter-clockwise. The mere fact, that the symbolic denotations of the two representations are different, should make it evident to anybody, that the difference is not a mere difference in the direction of rotation, but a difference in the meaning of the vector.

In my opinion, the question is, whether we should have one vector representation, or two different forms of vector representations. Both, the crank diagram and the time diagram, represent sine waves about equally well. The crank diagram, however, is practically limited to the representation of sine waves, while the time diagram, which is nothing but the standard system of polar coordinates of analytic geometry, can also represent complex waves and even nonperiodic phenomena, as they exist in alternating current circuits as electrical transients. As long as the electrical engineer will have to deal with distorted waves and with electrical transients, in their graphic representation the polar coördinates, that is, the time diagram will by necessity be used, and the question then is, whether the same diagram should also be used for sine waves, or whether in the crank diagram the students shall be made to learn a second form of representation.

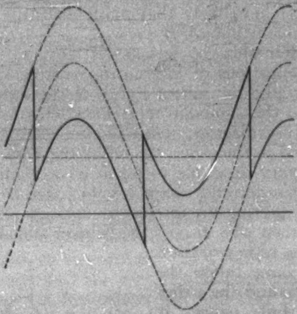

Fig. 2

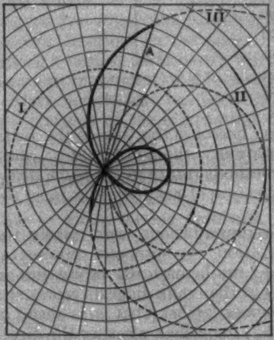

Fig. 3

An illustration of the representation of a distorted wave by the time diagram is shown in Fig. 5 of my discussion of " Vector

Power in Alternating Current Circuits", in the November PROCEEDINGS 1910 of the A. I. E. E., which is reproduced here as Fig. 1. The polar curve shows 5 extrema (maxima and minima) and thereby demonstrates the preponderance of the 5th harmonic.

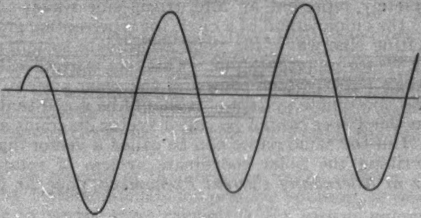

FIG. 4

Figs. 2 and 3 show the current in the armature conductors of a synchronous converter, Fig. 2 in rectangular coördinates, Fig. 3 in polar coördinates. Fig. 3 shows by the area of the curve the heating effect of the current, and demonstrates the great increase of the $i^2 r$ loss with increasing shift of the phase, that is, increasing shift of the line *A* from the vertical. Curve I gives the direct current circle, curve II the alternating current circle, and curve III the resultant, from which the line *A* cuts out the actual current, which latter is shown in heavy drawn line.

Figs. 4 and 5 show the starting transient of an alternating current in an inductive circuit, in rectangular and in polar coordinates. Fig. 5 is interesting in illustrating the apparent phase advance of the current waves (2) and (4), which represents the power increase corresponding to the storage of energy in the magnetic field.

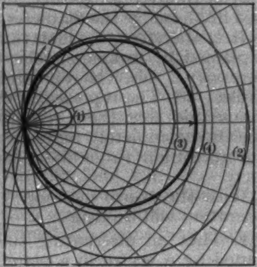

FIG. 5

Louis F. Blume (by letter): When either the clock diagram or polar coördinates are employed to graphically represent alternating current phenomena, two ideas are involved. First—a characteristic which represents the alternating sine wave, and second—a mechanism by which the characteristic is subjected to a definite action. In the clock diagram the mechanism is the rectangular system of coördinates and the characteristic the straight line. In the polar coördinate system the mechanism is the rotating radius vector and the characteristic is a circle. In the clock diagram the vector when subjected to the idea of rotation and projection will completely represent an alternating sine wave, and in the polar coördinate system the circle when subjected to the idea of the intercept of a rotating radius vector will completely represent an alternating sine wave.

But, by the employment of a circle for representing graphically an alternating sine wave, the polar coördinate system does not result in a vector representation. This fact is excellently shown in Dr. Berg's paper, which compares the polar system with the rectangular coördinate system. It should be noted that Figs. 2, 3 and 4 in this paper cannot be called vector diagrams any more than Fig. 1 in the same paper can be called a vector diagram.

In describing the polar coördinate system of rotation, Dr. Steinmetz in *Alternating Current Phenomena*, page 20, gives the following:

"The characteristic circle of the alternating sine wave is determined by the length of its diameter—the intensity of the wave; and by the amplitude of the diameter—the phase of the wave.

"Hence, whenever the integral value of the wave is considered alone and not the instantaneous values, the characteristic circle may be omitted altogether, and the wave represented in intensity and in phase by the diameter of the characteristic circle."

It is therefore, evident that if vector representation is to be explained by means of polar coördinates, two distinct steps are necessary. 1st. The representation of the alternating value by a circle. 2d. The representation of the circle by its diameter. In the second step there remains the difficulty that the diameter does not completely represent the circle, and therefore only gives the maximum value and phase relation of the alternating sine wave.

With the above mentioned facts in mind, the following consideration will be clear.

1. That an alternating sine wave can be completely represented by a vector in a plane, is an established fact.

2. The clock and the polar coördinate methods are simply different means of explaining that fact.

3. To explain the fact by the polar coördinate method, requires two distinct steps, 1—that an alternating quantity can be represented by a circle, and 2—that the circle can be represented by its diameter.

4. The diameter of the circles does not completely represent the circle, and on that account only gives the maximum value and phase angle of the wave.

5. The diameter of the circle cannot be considered as a vector in the ordinary sense, for it cannot be moved to any parallel position without disturbing values of the intercepts.

6. It seems therefore, that it is impossible to fully demonstrate

the fact that an alternating sine wave can be completely represented by a vector by using the ideas of polar coördinates alone.

7. The ideas involved in polar coördinates cannot therefore, be logically offered as an argument for the employment of a particular convention in vector diagrams.

As given by Dr. A. E. Kennelly in his recent article on Vector Power (A. I .E. E. PROCEEDINGS, July, 1910), the clock diagram is used to explain vector representation, on the one hand by assuming a rotating vector and a fixed axis of projection; on the other hand by assuming a fixed vector and a rotating axis of projection. The direction of rotation in either case may be clockwise or counter clockwise. In this connection the following is suggested.

1. That on account of the universal use of counter clockwise rotation by mathematicians for positive rotation, it would seem preferable to use the same convention for vectors unless there is good reason to employ the opposite convention.

2. That since it is almost the universal practice, on account of greater simplicity, to consider an axis of reference as stationary, it therefore seems preferable in vector representations to refer to a stationary axis unless there is some good reason for employing the opposite convention.

O. J. Ferguson (by letter): In a discussion of the different systems of representing periodic functions, it may prove of value to outline some of the pros and cons and comment upon them briefly. In the following summary, points favorable to the use of the system are listed in the positive column. Unfavorable points are listed in the negative column. Not much can be determined by the comparison of the number of points, favorable or unfavorable, as some of those mentioned should be given much more weight than others. In the long run, however, systems should be compared by their relative total weights. No attempt has been made to attach such weights at this time as each person using any of the methods must determine that matter for himself.

POSITIVE	NEGATIVE
Rectangular Coördinates.	
1. Concept of continuance of time	1. Impossibility of graphical methods of calculation.
2. Transient phenomena.	2. Inconvenient methods for combining waves analytically.
3. Non-sinusoidal waves.	
4. Direct evaluation.	
5. Visual comparison of successive instantaneous values.	
6. Summation of waves at any instant.	
7. Recognition of higher harmonics.	
8. Based upon a coördinate system.	

Positive	Negative
Polar Coördinates.	
1. Based upon a coördinate system. 2. Complete periodic cycle may be shown. 3. Periodicity of cycle. 4. Permanency of cycle. 5. Direct evaluation when complete curve is used. 6. Transient terms. 7. Summation of waves at any instant, when complete curve are used. 8. Derivation of effective value, etc. 9. Use of vectors. 10. Equivalent sine wave. 11. Graphical calculations and imaginaries may be used.	1. As vectors, the summation of instantaneous values is not direct. 2. Visual comparison of successive instantaneous values is difficult.
Crank Diagram.	
1. Periodicity of cycle. 2. Graphical calculations and complex imaginaries may be used. 3. Easy visual comparison of successive instantaneous values by projection. 4. Summation of waves at any instant by projection.	1. A mechanical device for representing harmonic motion. 2. Complete cycle not shown. 3. Dual line position. 4. Evaluation of instantaneous values by indirect methods, as projection. 5. Suitable for sine waves only.

RECTANGULAR COÖRDINATES

POSITIVE

1. The x-axis extends to infinity and thus forcibly draws the attention to the continuance of time.

2. With the passage of time emphasized as above, transient phenomena are well shown.

3. Periodic deviations from sine waves are likewise easily recognizable.

4. Inasmuch as the curve is fully drawn, it is a simple matter to evaluate the function at any instant.

5. Ordinates, being parallel lines, are easily compared for their relative magnitudes.

6. In adding waves, their ordinates combine directly.

7. Many of the higher harmonics are easily recognized and they all have simple analytical expressions.

8. The whole conception is based upon a regular system of coördinate geometry.

NEGATIVE

1. It is very convenient to be able to represent the given function by some one thing (as a vector, in other systems) and use this thing for graphical calculations. This system does not admit such simplification.

2. The addition of waves analytically is not a simple process. That is, if

$$\sin \overline{\phi + 30^\circ} + \sin \overline{\phi - 15^\circ} = A \sin \overline{\phi + \alpha},$$

the evaluation of A and α is not as simple as the graphical solution nor does it appeal as quickly to the eye as does the latter.

Polar Coördinates

POSITIVE

1. The conception is based upon a regular system of coordinate geometry.

2. With periodic functions, the complete wave may be shown, whether it is regular or irregular in shape.

3. Angles above 360 degrees indicate a recurrence of the cycle, or periodicity of the function.

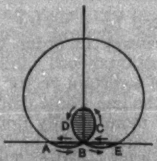

Fig. 1.—*A B C D B E B A.*—Current cycle in the center coil of the phase of an n-ring converter.

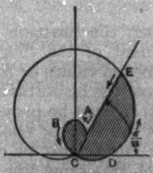

Fig. 2.—*A B C D E A.*—Current cycle in the end coil of the phase of an n-ring converter.

In each figure, the curved portion is taken at one sweep and the rectilinear portion occurs at the commutation point, or as the coil passes a brush. The complete curve, the limacon, is represented by the equation

$$I = I_1 \sin \theta \pm \tfrac{1}{2} I_0$$

where I_1 is maximum alternating current component and I_0 is direct current current

4. The presence of a single closed curve indicates the repetition of the cycle, or the permanency of the function.

5. The instantaneous value is directly obtainable for any time, along the radius vector corresponding to that time.

6. Transient phenomena shown thus give a direct comparison of successive cycles, indicating the waning of the transient term and the departure from the permanent cycle.

7. The summation of any number of waves is accomplished by the addition of their vectors.

8. The effective value of the function is readily obtained by the planimeter, which is of value in various calculations. For example, if a railway motor is rated in terms of its continuous current carrying capacity at the given voltage, plotting the variable current cycle by polar coördinates is a direct means of establishing a rating for the given motor or of choosing a motor to fit the given conditions.

Another instance may be taken from the field of synchronous converter phenomena. The accompanying figures show current cycles for the end coil and for the center coil of the phase of a converter armature winding. The enclosed areas vary as the square of the radius vector, that is, as i^2. The relative areas represent, therefore, relative heatings. Variation in the number of rings, change of power factor, choosing other coils of the armature, etc., may all be illustrated by their respective effects upon the polar diagram.

9. Sinusoidal functions may be represented by vectors, retaining the fundamental idea of the polar diagram. There is no change of view point.

10. A definite meaning can be given to the term "equivalent sine wave" in terms of equivalent areas.

11. The system lends itself readily to graphical calculations and to the use of the complex imaginary expression.

NEGATIVE

1. When the function is represented by a vector, a further development of the diagram is necessary in order to obtain instantaneous values or to combine instantaneous values. That is, to know the instantaneous value of a certain vector quantity, either (*a*) it must be projected upon the line whose displacement indicates the time or epoch, or, as is more usually done (*b*) the complete curve must be conceived as cutting off the infinite extension of this same line and limiting its length. The limited length is the value sought.

2. In comparing successive instantaneous values of the function, it is more difficult to estimate their relative values when the two (or more) lines compared are divergent. Parallel lines are much more easily contrasted.

Crank Diagram

POSITIVE

1. Successive revolutions of the crank indicate a recurrence of the cycle or a periodicity of the function.

2. Calculations may be made either graphically or by the use of complex imaginary quantities.

3. Successive instantaneous values may be compared by projection upon the 90 degree line or by the relative heights of the vector arrow-heads above the initial line. In one case, the lengths are measured along the same line, while, in the other case, they are measured along parallel lines and, in either condition, inequality is easily recognized.

4. After projection upon the 90 degree line, instantaneous values may be added, directly. (This seems slightly simpler than having to project upon the general vector or than drawing the full curve.)

NEGATIVE

1. The conception used is that of a crank revolving mechanically, one component of its extension illustrating harmonic motion. As such, it is effective but its range beyond a few of the general applications is limited. It is proper to note that the limited range does cover the most common and, probably, most useful applications of the vector principle.

2. The complete cycle cannot be represented by any curve upon the diagram, as all instantaneous values are measured along the same line—the 90 degree line.

3. The complete concept of the function, as regards phase and magnitude, requires *two* elements for its expression. That is, a *crank position* represents phase condition, while the magnitude of the variable is indicated by a *length along a different line.* This is in contradistinction to a vector which represents phase condition (epoch) by position and also shows magnitude by its own length.

4. As a result of the inability to show the complete curve, instantaneous values can be obtained only by projection.

5. It cannot properly be called a system for representing *periodic* functions but must be limited to *sinusoidal* functions. Transient terms, higher harmonics, converter current cycles, etc., can not be exhibited.

The point at issue in the discussion before the Institute is as to the relative values of the *crank diagram* and the *vectorial side of the polar diagram*. Inasmuch as the polar diagram is broad enough to cover the whole field *including* vector representation, and it must be used for certain purposes quite beyond the range of the crank diagram, is it not advisable to meet on the common ground of the most usable system? In some problems, polar coördinates have decided advantages over rectangular coordinates. Shall we depend wholly upon the latter and the crank diagram, to the exclusion of the polar system? Or, are we best served by keeping all three schemes in mind in a more or less muddled condition? Undoubtedly, usage is what will settle the question and, probably, the engineering public will standardize what they wish.

C. A. Adams (by letter): Arguments on both sides of this question have been in print for some time, and it seems undesirable to take the subject up at any length at this late hour. I should like, however, to present one argument, which, as far as I know, has not been presented before.

It is claimed for the polar coördinate method of representation, that the root-mean-square value may be readily determined by planimetering the polar curve of the alternating quantity in question; but this is only occasionally desirable, and then only in the case of a complex wave, in which case the polar curve is not a circle and therefore has no diameter by means of which it can be represented. In fact the representation of alternating currents or e.m.fs. by vectors, ceases to be in any sense exact when the quantities in question deviate much from the simple sinusoidal type; but when such deviation exists, we can handle the problem satisfactorily only by the aid of harmonic analysis, practically all of the methods of which require the wave to be plotted in *rectangular* coördinates.

But after all the question at issue must finally be settled by usage rather than by arguments based on any fundamental merits of the case; it is a conventional part of our alternating current language upon which we must agree, if we are to avoid an enormous waste of energy on the part of all students of this subject. I for one will gladly abide by the general consensus of opinion if it can be obtained, even though it involves a reversal of my habitual notation.

We talk much about the efficiency of apparatus, and make much of a saving of one per cent but we keep on using mixed systems of notation and of units, which involve a much larger reduction in the efficiency of the engineer himself.

A paper presented at the 258th meeting of the American Institute of Electrical Engineers, Boston, February 17, 1911.

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ECONOMIC LIMITATIONS TO AGGREGATION OF POWER SYSTEMS

BY ROBERT A. PHILIP

Limitations on the distance to which power can be transmitted electrically have been investigated from time to time. In this paper it is the purpose to point out that the limiting distance of transmission is not the limit of economical interconnection and that there is probably no such limit. It is also the purpose to outline certain principles of electric transmission which indicate the line along which unlimited extension of electric networks may proceed.

Electric power promises to become the universal power of the future. It is not a substitute for steam power or water power; it competes with no prime mover. Electric power is essentially a secondary power. Prime movers produce useful but crude mechanical power from the rough, irregular forces of nature. Mechanical power, transformed and refined in the electric generator, becomes electric power, the highest known form. The highest form because it can be changed to other forms, heat, light, motive power, chemical action with unparalleled directness and simplicity. It is the uniform method of applying any kind of power from any source to any work. To other powers it stands as a common medium of exchange. Prime power is like property, electric power like money.

The electric motor consumes electric power produced by an electric generator driven by a prime mover. When an electric motor is substituted for a steam engine the load is merely transferred from one prime mover to another. There is a loss of power in the electric generator, a loss in the electric transmission line and a loss in the electric motor. In spite of these losses electric transmission and distribution of power is commercially successful because of economy, flexibility and cleanliness.

The motor is economical merely because the prime mover on which it ultimately depends is still more economical; that is, electric power is an advantageous means of producing competition between different prime movers and thereby displacing those that are wasteful. Every circumstance unfavorable for economical power generation can be found in varying degrees among isolated plants while central electric generating plants may take advantage of every practicable economy. Certain highly important differences favorable to centralized prime movers are greater size, greater diversity factor, greater load factor, convenient location for fuel and water and cheap land. Of these some are automatically cumulative. As the plant grows its economy increases and as the economy increases it surpasses that of more and larger isolated plants, displaces them and thereby grows some more. Furthermore, electric power is not limited to bringing a large prime mover into competition with a small prime mover of the same kind; it goes farther, taking for its source any other kind of prime mover which may be more economical. The economy of electric power is essentially progressive and is only limited by that of the best prime mover of any size, any kind, anywhere.

Power is used to produce results. The requirements for economical production and economical application of power are antagonistic. Concentration and continuity are essentials for favorable production, while subdivision and controllability best adapt it to its uses. Electric power reconciles these diverse requirements. While concentrated at the continuously running generator, it is subdivided at the intermittently running motors.

Essentially a secondary power, it consumes no raw material and emits no waste material. No water or fuel goes in, no ashes, water or gases come out. Increased human activity and efficiency require and depend on increased power, per capita, per square mile, per cubic yard. Contamination of the air by prime movers sets an artificial limitation to beneficial concentration. Electric power removes the limitations and opens up new possibilities. The modern city subway can be operated by electricity and by that alone.

The principle underlying the success of electric power is that of uniformity. Incidentally, to be uniform, the method must be indirect. The same principle underlies the use of money.

Property may be exchanged directly by barter, but the uniform method of indirect exchange by purchase and sale is superior. In each case the intermediate medium of exchange gives the flexibility necessary for equalizing production and consumption on a large scale. The public service corporations which distribute power have a function analogous to a banking system. They constitute clearing houses for balancing the individual increases and decreases of power requirements of a community as a whole and provide a centralized reserve for meeting promptly any total net increase.

The power plant which does not use electric power stands alone. In the continual readjustment of industry, there are shifting deficiencies and surpluses of power which cannot be economically met by increasing, decreasing and moving local prime mover power plants. In the aggregate, the disproportion of the isolated prime movers to their loads must be enormous. This leads to the conclusion that there is a great collateral advantage in using electric power, wherever practicable as an intermediate step between the prime mover and the work, thereby providing the necessary means of immediately and without further expense participating in the advantages of uniting resources with the rest of the community whenever emergency, convenience or economy require it.

The success of electric power distribution and transmission has been due largely to two specific applications of the underlying principle of uniformity. First, that it is cheaper to generate power by steam in one large plant than in numerous little plants. Second, that steam power may be economically superseded by otherwise impracticable water powers. These two applications have built up two classes of transmission systems, those from central steam plants originating at the large centers of population and radiating into the country where they supply current for railways, light and power in outlying towns and villages; those from water powers starting from the mountains and converging toward the cities. These applications alone, though stimulated by increased consumption and higher price of fuel, may extend the economical radius of transmission, but not indefinitely.

On the other hand, if there is no increase in the economical radius, nevertheless, the continued development which may be reasonably expected along present lines will in time cover the country with high-tension distribution and transmission lines.

These lines will form short contiguous but independent transmission systems each one having a specific function of distribution or transmission which pays for the interest on the investment the repairs and maintenance and the cost of power used up in core loss and other friction or leakage necessary for keeping the system alive. While each line is useful and necessary, every line is subject to periods when it is idle. In other words, its load factor is low. During off peak hours, power can be transmitted subject to no charge for interest, repairs or maintenance and free of deduction for the constant losses of the system. Devoid of these encumbrances, the usual limitations to the distance to which power may be transmitted do not hold.

This opens the way to a broader application of the principle of uniformity. The differences in economy between large and small steam plants and between steam and water power plants are not the ultimate limitation to transmission. Were the limitations reached in these two directions there remains a vast field of economy in applying the principle in other directions.

Diversity factor alone contains almost inconceivable possibilities. Wherever there is intermittent work diversity factor may be expected. In so far as it is unnecessary to do two different things simultaneously it should be unnecessary to duplicate the power supply. Since the point of application of electric power may be instantly transferred from place to place, only a half (or other fraction, as the case may be) of the prime power is required in a central plant which would be needed in two or more separate local plants. This fraction is the diversity factor. It has already done much to enhance the advantage of the large plant over the small one but the large plants in turn are governed by local conditions and, like the isolated plants they supplant, they have important diversity factors among their loads. Thus the conditions determining the hour of peak vary considerably in different cities, with the industries and customs of the inhabitants, with local weather conditions, with the altitude, latitude and longitude; the artificial convention of standard time makes an hour's difference in time of starting work in nearby cities and over greater distances the natural difference in time makes greater differences.

Water powers have a peculiar species of diversity factor of production due to non-coincidence of deficiencies. While there are dry years in which all water powers may suffer deficiency, the idea of coincident deficiencies is largely due to insufficient and inaccurate records. From the nature of the case the rains, snow fall, freezing and thawing must vary widely according to the location and exposure of the watersheds. There will be some diversity between the flow of any two streams though they be adjoining, a greater diversity between those on opposite sides of a divide, and more between those on different mountain groups. A large river which runs dry for short periods for lack of storage and a large reservoir on a small stream are each defective for power supply, but together they may be mutually supplementary. By combination the bulk of the power may be derived from rivers on one watershed, the reserve storage from those on another.

Economy of reserve is another application. The large plant gives centralized reserve, the large system gives a diversity factor among accidents and an interchange of reserve.

More remotely the general extension of transmission may open up possibilities of developing the intermittent powers of nature which, variable and unreliable in any one locality, may, taken over a large area, or in connection with each other or with existing developments, be found to be uniform and reliable. Thus the tides occur at different hours at different points. Variable powers such as the wind have appeared impracticable largely because they have never been studied adequately, and if developed locally, require a prohibitive expense for regulating, equalizing and storage. Comprehensively developed as an auxiliary to an established system which could use the power as available, the cost of power from these sources would be far less than has been heretofore supposed.

Transmission lines are the highways of power. Having made power portable and universally applicable by reducing it to the electric form, it is inconceivable that the highways over which it travels will not be vastly more useful if interconnected.

More definitely, there is the present problem of existing transmission systems growing beyond the bounds for which they have been designed by the annexation of adjoining independent systems as one by one the collateral advantages pass into the domain of accepted fact.

To design a transmission line to transmit power from a water power plant to a city is a definite problem. To interconnect two such lines to accomplish some auxiliary purpose not in the original design is quite a different problem. The interconnection of two transmission systems is like combining two railroads, first, there must be a physical connection, then unified operation. As the gauges of the railroads must be reconciled, so the frequencies, phases and voltages must be adapted by reducing to a common standard or the power must be converted at the junction points. Then the flow of power in the network must be controlled so that, within the limitations of the wires provided, power may be transferred at will from points of surplus to those of deficiency. This problem of interconnection differs from that of transmission in introducing as an element the idea of reversible transmission, that is, either end of the line may be generating or receiving end.

The interconnection of two systems forecasts future connection with a third and fourth. Such extension carried on indefinitely, leads to the conception of a single vast system which may be built up in the future. Electric power is successful because it is the one uniform method of equalizing supply and demand. Every extension and interconnection broadens the field in which it can act and should increase its success. Continued, indefinite extension is desirable and inevitable if possible.

As electric power is like a common denominator to which all other power is reducible, so alternating current is the common form to which electric power itself must be reduced to become universally available. Direct current is useful and necessary but its function, for the present at least, is that of a form auxiliary to or derived from alternating current and limited in the distance which it can travel to a single locality. Alternating current combines a suitability to the high pressure necessary for transmitting power in bulk long distances with a simplicity of division and subdivision both of power and pressure which is necessary for the ultimate distribution. Furthermore, the alternating current system has unique qualities which especially suit it for reversible operation, and thereby adapt it for indefinite extension.

Electric currents are commonly regarded as flowing from points of higher potential to those of lower potential. With direct currents the potential of the generating end of the line must be higher than that of the receiving end directly in proportion to the power delivered in order to overcome the line resistance. With alternating currents delivering the same power over the same line at the same voltage and at unity power factor, the potential of the generating end must be still higher as the reactance as well as the resistance of the line must be overcome even if the power is delivered at unity power factor, which is usually regarded as the most favorable case for alternating transmission. If the power is delivered to an inductive load the power factor will be lower than unity and the potential of the generating end must be higher yet in order to force the magnetizing current over the line in addition to the working current.

To provide for the variation of drop of potential in a transmission line at varying loads numerous devices are used. The generator voltage may be varied through adjustment of the field rheostat or by compounding; the ratio of step-up and step-down transformers may be made different so that the generator voltage will be the same as the receiver voltage at full load instead of at no-load, as would be the case if the transformers had the same ratio; or separate boosting transformers may be used to the same end; a regulating dial connected to taps to the transformer windings may be used to vary their ratio, or a regulator consisting of a separate transformer of variable ratio may be used for the same purpose.

While in ordinary alternating-current transmission supplying only lights and induction motors the potential at the generating end is necessarily higher than at the receiving end, in a transmission line supplying a synchronous motor taking a leading current the condition may be reversed and the potential may be higher at the receiving end than at the generating end so that the current flows from a point of lower to one of higher potential.

While leading currents may cause the potential at the receiving end to be higher than at the generating end they do not do so necessarily. With a large amount of leading current the potential may be higher at the receiving end but with a small amount it may be lower and with an intermediate amount it may be the same at the two ends and may be maintained the same even if the load varies by a corresponding variation in the amount of leading current.

Power may therefore be transmitted over a line by alternating currents without change of potential and a system may be built up by adding other lines until a network is formed uniting many power houses and many substations. In such a system the potential may be the same at the bus bars of every power house and every substation and yet power may be transferred at will through the network in any direction. Since the potential at the edges of such a network is the same as at the center it is evident that the system is capable of indefinitely great extension. While the power is transmitted without loss of potential there is a loss of energy equal to the square of the current multiplied by the resistance as usual. The possibility of extension is not for the transmission of power in bulk for indefinitely great distances but rather for the extension of a network containing points of generation at intervals, the load being equalized on the points of generation by means of the network which permits of power being transmitted to or from any point in any direction for distances as great as considerations of emergency or economy may indicate from time to time.

In view of the customary drop of potential from the generating to the receiving end of the line, transmission without this drop may at first seem to be an abnormal and unstable condition but this is not the case.

Suppose two identical machines connected by a line, one run as an alternator and the other as a synchronous motor. If the resistances and reactances of the armatures are so small as to be negligible and if the strengths of the fields are so great compared to that of the armatures that the effect of armature reaction is negligible then this combination will automatically transmit the power with constant potential at each end of the line independent of load and of line impedance. If the armatures of the machines have appreciable resistance or reactance there will be a drop of potential from no-load to full load but it should be noted that the drop results from the resistances and reactances in the machines, not those in the line. It is therefore only necessary to improve the regulation of the machines themselves to attain a natural constant potential transmission system.

To operate a synchronous motor on the constant-potential system we should therefore adjust its field, not according to a power factor meter but according to a voltmeter on the line as it is normal line voltage, not unity power factor on the motor, which is desirable. The condition, previously assumed, that the synchronous motor is a machine which is a duplicate of the generator is not essential, also any other kind of load may at the same time be supplied by the same line. Where both synchronous and induction motors are operated from the same line the voltmeter method of adjustment has the advantage of simplicity in that the proper adjustment of the field of the synchronous motor for overcoming the lagging currents of the induction motors is obtained thereby although the currents taken by the induction motors are unknown to the one making the field adjustment. Where synchronous motors are used on lighting systems the advantage of operating them on the constant potential system is obvious for if correctly operated in this manner the regulation of the system, which is of prime importance, becomes perfect.

Taking again the case of the two-machine transmission just considered. Suppose a mark made on some point of the rotor of the generator and a similar mark at the corresponding point of the rotor of the motor. At no-load the marks will reach the top of the circles in which they revolve at the same time indicating that the voltage of the motor is in phase with that of the generator; as the load comes on the mark on the motor will fall behind that on the generator, reaching the top position a little later, indicating that the voltage of the motor is falling behind that of the generator. This illustrates the principle that in constant-potential transmission current flows and power is transmitted from points of advanced to those of retarded phase. In other words the potential of the receiving end must drop behind that of the generating end in phase instead of below it in magnitude.

In a direct-current transmission with constant generator potential the amount of power transmitted increases with increased drop of potential up to a certain maximum and then decreases again, so with constant potential alternating transmission the amount of power increases with increased retardation of potential phase up to a maximum and then decreases again. In each of these cases the range from no-load to the maximum load is the range of stable operation, beyond the maximum is a range of unstable operation. In each case too, the maximum power which may be transmitted depends on the constants of the line. The greater the resistance the less power that may be transmitted by either direct or alternating currents. The analogous assumption that the greater the line reactance the less the power that may be transmitted by alternating currents is incorrect. With no line reactance no power could be transmitted at constant potential, but as all lines have some reactance this case would never actually occur. Up to a certain limit the greater the line reactance the greater the maximum amount of power which may be transmitted. For every transmission line there is therefore a range of stable operation for constant potential transmission.

The utility of a system of transmission depends partly on the ease with which its operation can be foretold by calculation. On this basis the constant potential system is at a great advantage for its characteristics can be shown in a simple diagram constructed from constants which are readily calculated and have an easily understood physical meaning.

Geometrically the flow of power is represented by straight lines and circles, algebraically by quadratic equations both expressed in terms of the amount of power the line takes when short circuited.

The calculations and the conclusions from them are given in more detail in a supplement to this paper. The results show that:

The constant potential alternating system is on a par with direct current as to the amount of power and as to the efficiency of transmission over a line of given resistance and voltage.

A comparatively high line reactance is a favorable feature both as regards amount and efficiency of power transmission and therefore a frequency of 60 cycles per second may be better than one of 25 cycles for power transmission.

Reactance makes a line opaque to short circuits but wattless power introduced at the receiving end makes it transparent to the flow of useful power, therefore the power at short circuit may be less than at full load.

A short circuit may be a local matter not interrupting the service of the system as a whole, not affecting the voltage except for a limited radius, and not draining any extraordinary amount of power from the system.

Switches of limited capacity may be safely used on systems of unlimited power.

Blocks of power too great to be safely controlled may be subdivided by artificial lines instead of being entirely separated.

There are no limitations to amount of phase difference, therefore none to unlimited extension at constant potential, but in distant parts of a large system the difference may be so great that one machine may be one or more complete cycles (or even revolutions) behind another.

In interconnecting different branches of a large system the actual as well as the apparent phase difference must be considered, therefore the readings of any ordinary synchronizing device may fail to indicate the true phase relation.

Constant potential transmission requires controllable leading currents, synchronous motors are the practical source of such currents, therefore the first step in establishing such a system is to have as large a part of the receiving equipment as possible composed of synchronous motors, to have these motors designed for carrying full load with leading currents of say 80 per cent power factor, and to have their voltage controlled by non-compounded voltage regulators.

Rotary converters are synchronous motors, but as ordinarily constructed are poorly adapted for operation with leading currents.

The electrostatic capacity of transmission lines furnishes leading currents which are not directly controllable and are therefore not the equivalent of those from synchronous motors.

Synchronous motors can take lagging as well as leading currents, but the lagging currents taken differ from those of induction motors in being controllable.

The leading currents of line capacity and the lagging currents of induction motors subtract and add respectively certain amounts to the available leading currents to be furnished by the synchronous motors, that is, they do not affect the range of control required but rather shift the mean position of this range toward lagging or leading respectively.

To summarize the principles here outlined. First is that of the solidarity of the power market as a whole, next is that of the place of electric power in this market which, not itself a prime power yet is the common medium of exchange for all prime power. From this follows naturally the indefinite extension and interconnection of transmission lines, the highways of power. Underlying all these is the requirement that electric power though poured in unlimited amounts into a system of indefinitely great extent must be as mobile as the trains on the country's railroad network, must be universally uniform in quality, must never be totally interrupted and though in amount unlimitedly great must not be uncontrollable. To meet these requirements electric power must take the alternating-current form and should be transmitted on the constant-potential system. Finally, this system is one using high line reactance made transparent by leading wattless currents and transmitting power by displacing the phase of the voltage instead of varying its amount.

SUPPLEMENT

Below are developed certain formulæ for the transmission of power by alternating currents at constant potential.

Before deriving the formulæ for the construction of the diagram the meaning of the constants in terms of which the results will be obtained may be explained and their method of calculation shown.

We are now considering a certain line (single-phase) which is to be operated at a constant potential E. The resistance of the line is R, its reactance X and its impedance Z; these are calculated from tables in the usual way by multiplying the tabulated values per unit of length by the length of the line.

Consider now that one end of the line is maintained at potential E and the other end short circuited. A short circuit current I will flow. By the analogy to Ohm's law which holds for alternating currents, the current I is equal to the potential divided by the impedance or E/Z. To maintain this short circuit current requires power equal to $I\,E$ or its equivalent $I^2\,Z$ apparent watts. The apparent watts $I^2\,Z$ for which we may write W_3 are composed of two components, the "true" watts $I^2\,R$ and the "wattless" watts $I^2\,X$ for which we may write W_1 and W_2 respectively.

Consider next that the potential at one end of the line is maintained at the same potential E but with direct instead of alternating current, and the other end is short circuited as before. A short circuit current I' will flow. By Ohm's law the current I' is equal to the potential divided by the resistance or E/R. To maintain this short circuit current requires power equal to $I'\,E$ or $I'^2\,R$ watts. For this power absorbed by the short circuit current we may write W.

The four constants W_1, W_2, W_3, and W are all that are required for the construction of the constant potential transmission diagram. They are interpreted physically as power absorbed by the line at short circuit. The first three are respectively the "true", "wattless" and "apparent" power absorbed at short circuit with alternating current and the last one is the power absorbed at short circuit with direct current. Of the four constants there are really only two independent, the other two being used for simplicity and symmetry of expression and for aid in the physical interpretation of the resulting equation. Thus any two may be eliminated by the use of the relations shown algebraically in equations (**16**) and (**26**) given hereafter, or shown geometrically by the two equivalent constructions illustrated in Fig. 2 and Fig. 3, respectively.

The derivation of the formula for the constant potential transmission diagram is from the auxiliary voltage diagram shown in Fig. 1 as follows:

Fig. 1 represents the voltage relation in a line transmitting any amount of power (say w_1) at constant potential. In addition to the true power w_1 delivered there will also be of course a wattless component w_2, the resultant of the two components being the apparent power w_3 delivered.

The voltages at the generating and receiving end are each equal to E. That at the receiving end is behind that of the generating end by the angle θ. The current i is necessarily leading at the receiving end and is ahead of the potential at that end by the angle α. The cosine of α is therefore the power-factor of the receiving end and the sine of α is the inductance factor. The potential at the receiving end being out of phase with that of the generating end there is a difference of potential e between the two ends of the transmission line in spite of the fact that the potentials at the two ends are numerically equal. Since the line is necessarily inductive the current i must lag behind the potential e by an angle ϕ. The cosine of ϕ is therefore the power factor of the line itself and the sine of ϕ its inductance factor. The diagram is now completed by drawing lines showing the resolution of the received voltage E and line voltage e into components in phase with and in quadrature with the current and by drawing a line bisecting the angle θ which line consequently becomes a perpendicular to e.

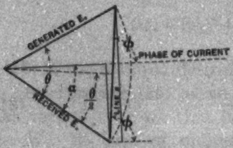

Fig. 1.—Voltage diagram

From the diagram we find by elementary geometry:

$$\alpha - \frac{\theta}{2} = \frac{\pi}{2} - \phi \tag{1}$$

By trigonometric reduction of (1):

$$\sin\frac{\theta}{2} = -\cos(\alpha+\phi) \tag{2}$$

$$\sin\frac{\theta}{2} = \sin\alpha\sin\phi - \cos\alpha\cos\phi \tag{3}$$

From the diagram again:

$$\sin\frac{\theta}{2}=\frac{e}{2\,E} \tag{4}$$

From the law of the alternating circuit applied to normal and short circuit conditions respectively:

$$e=i\,Z \tag{5}$$

$$E=I\,Z \tag{6}$$

Changing e/E by substituting values given in (5) and (6), transforming algebraically and using definitions of w_3 and W_3 as apparent watts:

$$\frac{e}{E}=\frac{i\,Z}{I\,Z}=\frac{i}{I}=\frac{i\,E}{I\,E}=\frac{w_3}{W_3} \tag{7}$$

Substituting (7) in (4):

$$\sin\frac{\theta}{2}=\frac{w_3}{2\,W_3} \tag{8}$$

From the definitions of power factor and inductance factor:

$$\cos\alpha=\frac{w_1}{w_3} \tag{9}$$

$$\sin\alpha=\frac{w_2}{w_3} \tag{10}$$

From the fact that the power factor and inductance factor of the line are the same at all loads including short circuit:

$$\cos\phi=\frac{W_1}{W_3} \tag{11}$$

$$\sin\phi=\frac{W_2}{W_3} \tag{12}$$

Substituting (**8**), (**9**), (**10**), (**11**) and (**12**) in (**3**):

$$\frac{w_3}{2\,W_3} = \frac{w_2\,W_2}{w_3\,W_3} - \frac{w_1\,W_1}{w_3\,W_3} \qquad (\mathbf{13})$$

By algebraic reduction of (**13**) :

$$w_3^2 = 2\,(w_2\,W_2 - w_1\,W_1) \qquad (\mathbf{14})$$

The relation between apparent power and its components is:

$$w_3^2 = w_1^2 + w_2^2 \qquad (\mathbf{15})$$

$$W_3^2 = W_1^2 + W_2^2 \qquad (\mathbf{16})$$

Substituting (**15**) in (**14**):

$$w_1^2 + w_2^2 = 2\,(w_2\,W_2 - w_1\,W_1) \qquad (\mathbf{17})$$

By algebraic transformation of (**17**):

$$(w_1 + W_1)^2 + (w_2 - W_2)^2 = W_3^2 \qquad (\mathbf{18})$$

(**18**) is the formula desired.

Interpreting (**18**) as an equation of a curve with w_1 and w_2 as variables we see that it represents a circle with its center at $-W_1$, W_2 and of radius W_3, therefore passing through the origin.

A diagram in which the power is represented by the position of a point, the rectangular coördinates of which are the true and wattless components of the delivered power may be called a power diagram. In such a diagram the polar coördinates of the same point represent by the radius the apparent power delivered and by the angle the phase difference between delivered current and delivered potential. Since phase difference between current and potential is determined by power factor it may be more conveniently designated by power factor as the angular coördinate.

We may now take a concrete example and construct the diagram. Take say a transmission line 11 miles (17.7 km.) long composed of two No. 0000 wires spaced 18 in. (45.7 cm.) on centers and assume that power is to be transmitted at 60 cycles per second at 11,000 volts.

From a table we find for No. 0000, 18-in. (45.7 cm.) spacing, 60 cycles:

Resistance 0.049 ohms per 1000 ft. (304.8 m.) of wire.
Reactance 0.106 " " " " " "
Impedance 0.117 " " " " " "

If impedance is not given it may be calculated from the resistance and reactance thus: $\sqrt{(0.049^2+0.106^2)} = 0.117$.

From these we compute for the line:

Resistance $0.049\times2\times5.28\times11 = 5.69$ ohms
Reactance $0.106\times2\times5.28\times11 = 12.3$ "
Impedance $0.117\times2\times5.28\times11 = 13.6$ "

The short circuit current would be
$11000/13.6 = 809$ amperes.

The power required to maintain the short circuit would be:

True power, $809\times809\times5.69/1000=3720$ kilovolt-amp.(kw.)
Wattless power, $809\times809\times12.3/1000=8060$ "
Apparent power, $809\times809\times13.6/1000=8900$ "

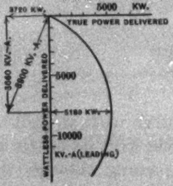

FIG. 2.—First construction of power diagram

The latter figure may also be computed more easily thus:

$809 \times 11000/1000 = 8900$ kilovolt-amperes.

The center of the circle is therefore at point -3720, 8060, and the radius is 8900, and we construct the diagram Fig. 2 accordingly.

We may determine the maximum amount of power which may be transmitted over the line at constant potential by inspection of the diagram as 5180 kw. A general formula for the maximum power may be derived from the diagram or from equation (**18**) rewritten as follows:

$$(w_1+W_1)^2=W_3^2-(w_2-W_2)^2 \tag{19}$$

Since W_1, W_2 and W_3 are constants $(w_1+W_1)^2$ and consequently w_1 will have a maximum value when $(w_2-W_2)^2$ is negative or a minimum. The square of (w_2-W_2) cannot be negative and its minimum value is zero, therefore the maximum value is given by

$$(w_1+W_1)^2=W_3^2 \tag{20}$$

or

$$w_1=W_3-W_1 \tag{21}$$

Stating this result in words: The maximum amount of power which may be transmitted over a line at constant potential and given frequency is equal to the difference between the apparent and the true power necessary to maintain the short-circuit current of the line at the same voltage and frequency.

The calculations made are all for single-phase circuits but they are equally applicable to three-phase, three-wire and two-phase, four-wire circuits of the same size wire and spacing by simply doubling the amounts of power in every case. This can also be done by giving the power diagram a double scale, making it applicable to single, two- or three-phase circuits.

We may next determine the influence which frequency has on the use of a line for constant potential transmission.

The resistance of the line may be taken as independent of frequency but the reactance and impedance will vary with the frequency and consequently the constants W_1, W_2 and W_3 will have different values for different frequencies.

The short-circuit condition for a direct-current line gives, from Ohm's law:

$$W = I'^2 R = \left(\frac{E}{R}\right)^2 R = \frac{E^2}{R} \qquad \textbf{(22)}$$

Similar equations for an alternating-current line are:

$$W_3 = I^2 Z = \left(\frac{E}{Z}\right)^2 Z = \frac{E^2}{Z} \qquad \textbf{(23)}$$

$$W_1 = I^2 R = \left(\frac{E}{Z}\right)^2 R \qquad \textbf{(24)}$$

Squaring (**23**) gives

$$W_3^2 = \frac{E^4}{Z^2} = \left(\frac{E}{Z}\right) . E^2 = \left(\frac{E}{Z}\right)^2 R . \frac{E^2}{R} \qquad \textbf{(25)}$$

Substituting (**22**) and (**24**) in (**25**) gives:

$$W_3^2 = W_1 W \qquad \textbf{(26)}$$

Substituting the value of W_3^2 in terms of its components:

$$W_1^2 + W_2^2 = W_1 W \qquad \textbf{(27)}$$

By algebraic reduction of **(27)**

$$\left(W_1 - \frac{W}{2}\right)^2 + W_2^2 = \left(\frac{W}{2}\right)^2 \qquad \textbf{(28)}$$

The latter is the desired relation. We see from it that the centers of the various circles representing the operation of the line at different frequencies lie on another circle whose center is at the point $\frac{W}{2}$, 0 and of radius $\frac{W}{2}$.

As an example we may construct the diagram for the line previously considered at various frequencies.

As previously computed we have, resistance, 5.69 ohms; the short-circuit (direct) current is, therefore,

11000/5.69 = 1930 amperes.

Power required to maintain the short circuit is

1930 × 11000/1000

= 21300 kw.

Taking half of this we have, 10650 kw.

The center of the new circle is therefore at the point − 10650, 0 and the radius is 10650 and the diagram is as shown in Fig. 4.

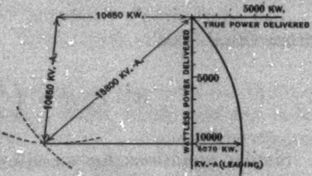

FIG. 3.—Second construction of power diagram

The construction of the diagram shows that instead of determining the location of the center of the circle representing the operation at a given frequency from the true and wattless components (W_1 and W_2) of the short-circuit power as previously done it may equally well be located from the (apparent) power necessary to maintain short circuit by alternating and direct current respectively (W_3 and W).

The use of this construction for determining the center of the circle when the transmission line already considered is operating at 25 cycles is shown in Fig. 3.

The complete calculation is as follows:

From the table we find for No. 0000, 18-in. (45.7 cm.) spacing, 25 cycles:

Resistance, 0.049 ohms per 1000 ft. (304.8 m.) of wire.

Impedance, 0.066 " " " " " "

For the line we compute
Resistance, 0.049×2×5.28×11=5.69 ohms.
Impedance, 0.066×2×5.28×11=7.65 "
The short circuit current is:
Direct current, 11000/5.69=1930 amperes.
Alternating current, 11000/7.65=1440 "
The power to maintain the short circuit is:
Direct current, 1930×11000/1000=21300 kw.
Alternating current, 1440×11000/1000=15800 kilovolt-amperes and 21300/2=10650 kw.

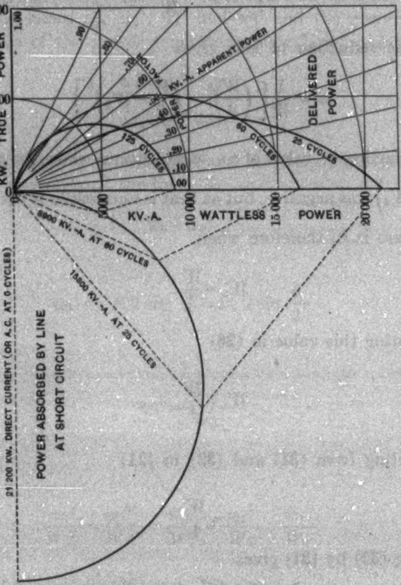
10 000
5000
0
KW. TRUE POWER
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
POWER FACTOR
KV.-A. APPARENT POWER
DELIVERED POWER
125 CYCLES
60 CYCLES
25 CYCLES
0
5000
10 000
15 000
20 000
KV.-A. WATTLESS POWER
8900 KV.-A. AT 60 CYCLES
15800 KV.-A. AT 25 CYCLES
21 200 KW. DIRECT CURRENT (OR A.C. AT 0 CYCLES)
POWER ABSORBED BY LINE AT SHORT CIRCUIT

FIG. 4.—Power diagram

Adding now to Fig. 4 the circles for 60 and 25 cycles as computed above and also adding that for 125 cycles computed in a similar manner, we find that for the particular line considered, more power can be transmitted (at constant potential) at 60 cycles than at either 25 or 125 cycles, the respective maxima being: 25 cycles, 4070 kw.; 60 cycles, 5180 kw.; 125 cycles, 3660 kw.

The amount of power which can be transmitted over this line at 25 cycles could be increased by artificially increasing the reactance of the line by the use of reactance coils.

To determine what frequency permits of the greatest amount of power being transmitted over any line (without the use of reactance coils) we take the previously written equations (**21**) $w_1 = W_2 - W_1$, and (**26**) $W_2^2 = W_1 W$:
Substituting values of W_1 from (**26**) in (**21**) gives

$$w_1 = W_2 - \frac{W_2^2}{W} \tag{29}$$

Algebraic reduction of this gives

$$w_1 = \frac{1}{W}\left[\left(\frac{W}{2}\right)^2 - \left(\frac{W}{2} - W_2\right)^2\right] \tag{30}$$

The maximum value of w_1 would occur when the square of $\left(\frac{W}{2} - W_2\right)$ was negative, but as that is impossible it occurs when the square is 0; therefore when

$$W_2 = \frac{W}{2} \tag{31}$$

Substituting this value in (**26**)

$$W_1 = \frac{W}{4} \tag{32}$$

Substituting from (**31**) and (**32**) in (**21**)

$$w_1 = \frac{W}{4} \tag{33}$$

Dividing (**32**) by (**31**) gives

$$\frac{W_1}{W_2} = \frac{1}{2} \tag{34}$$

Equation (**34**) may be stated as follows: The greatest amount of power can be transmitted over a line (at constant potential) at that frequency which makes the power factor of the line itself 50 per cent.

Since the greatest amount of power that can be transmitted over a line by direct current is one fourth of that necessary to maintain short circuit by direct current, equation (**33**) may be interpreted as follows:

The greatest amount of power that can be transmitted over a line (at constant potential) at most favorable frequency is the same as the greatest amount that can be transmitted over the line by direct current with the same initial voltage.

The formulæ given refer to delivered power; a similar relation holds for generated power. Thus, if the true, wattless and apparent line losses are w_1', w_2' and w_3' and the corresponding components of the power generated are, w_1'', w_2'' and w_3''.

$$w_1 = w_1'' - w_1' \tag{35}$$

$$w_2 = w_2'' + w_2' \tag{36}$$

From the equality of potential and current at the generating and receiving ends of the line:

$$w_3 = w_3'' \tag{37}$$

From Fig. 1

$$w_3' = i\,E\,2\sin\frac{\theta}{2} = w_3\,2\sin\frac{\theta}{2} \tag{38}$$

From (**8**)

$$w_3' = \frac{w_3^2}{W_3} \tag{39}$$

From this

$$\frac{w_3^2}{W_3^2} = \frac{w_3''^2}{W_3^2} = \frac{w_3'}{W_3} = \frac{w_2'}{W_2} = \frac{w_1'}{W_1} \tag{40}$$

These substituted in (**35**) and (**36**) give

$$w_1 = w_1'' - w_3''^2 \cdot \frac{W_1}{W_3^2} \tag{41}$$

and

$$w_2 = w_2'' + w_3''^2 \cdot \frac{W_2}{W_3^2} \tag{42}$$

Substituting these values in (**14**) gives

$$w_3''^2 = 2\left(w_2'' W_2 + w_3''^2 \frac{W_2^2}{W_3^2} - w_1'' W_1 + w_3''^2 \frac{W_1^2}{W_3^2} \right) \qquad \textbf{(43)}$$

Reduction of this gives

$$w_3''^2 = 2\,(w_1''\,W_1 - w_2''\,W_2) \qquad \textbf{(44)}$$

By algebraic transformation (**44**) may be rewritten

$$(w_1'' - W_1)^2 + (w_2'' + W_2)^2 = W_3^2 \qquad \textbf{(45)}$$

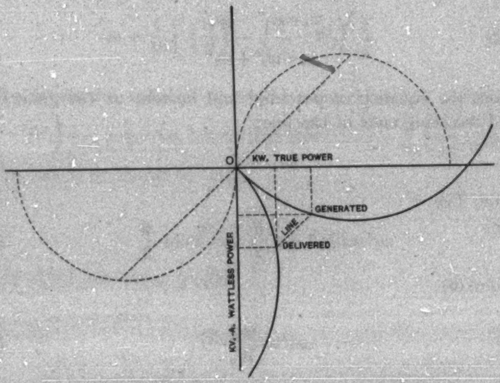

FIG. 5.—Power diagram—generated and delivered power

Interpreting (**45**), it is a circle of radius W_3 and center W_1, $-W_2$ passing through the origin. Similarly for a line with constant resistance, but variable reactance, (**45**) and (**28**) show that the centers of these various circles lie on a circle of radius $\frac{W}{2}$ and center at $+\frac{W}{2}$, 0. Fig. 5 is a power diagram for both the generated and delivered power. It consists of two equal tangent circles. From these it appears that with zero power delivered there is no wattless power at either end of line. With delivered power greater than zero there is always leading power required at the delivering end, but at the generating end it is first leading then lagging after passing through a point of unity power-factor.

A transmission line of adjustable reactance carrying a constant current (at constant potential) will have a constant input and an equal constant output of apparent power, but the true power output may vary from zero to a maximum due to varying power-factor. The current and resistance being constant, the line loss will also be a constant; therefore, the efficiency will be a maximum with maximum output. The input is equal to output plus line loss, and will be a maximum at the same time. The true input is also equal to the constant apparent input, less a reduction due to any wattless component. Consequently, maximum input, output and efficiency occur when the wattless component at the generating end is zero. Under these conditions the relation between generated voltage, generated and delivered current, generated and delivered true power, line loss and efficiency are the same as for direct current. Consequently, power can be transmitted by constant-potential alternating currents, or by direct currents at the same efficiency provided the line reactance is suitable.

At first sight the maintenance of constant potential by increasing the line reactance and by adding a wattless component to the delivered current in order to overcome the increased reactance would appear to produce an increased line loss. That this is not the case may be seen from the following considerations. With direct current or with alternating currents as ordinarily distributed, the line loss produces a drop in voltage; therefore, an ampere is not capable of doing as much work when delivered at the end of the line as when generated. If then, by any device it is possible to counteract the voltage drop so that the delivered voltage is equal to that generated, then the same work can be done with a smaller number of amperes delivered. The device actually used for this purpose is a wattless current and the total line loss due to the smaller working current, plus the additional wattless current, is no greater than before. While this device has neither increased nor decreased the line loss, it has made the voltage regulation perfect, a result impossible with direct current. That is, leading wattless power introduced at the receiving end of the line does not necessarily increase the line loss, in fact it may decrease the loss while either leading or lagging wattless power entering the line at the generating end does increase the loss. No reactance can therefore be found which will make the efficiency higher than that obtained when the wattless component is zero at the generating end. However, as with direct current, there are two currents each of which will deliver the same output with zero wattless power generated. One gives an efficiency of less and the other of more than 50 per cent. The latter, which gives the maximum efficiency for direct current, gives the true maximum for alternating current.

With a line of fixed reactance and with a load which gives zero wattless component at the generator, $w_3'' = w_1''$ and $w_2'' = 0$, substituting these in (**44**) and reducing gives

$$w_1'' = 2\,W_1 \tag{46}$$

substituting the same in (**40**) gives

$$\frac{w_1{}^2}{W_3^2} = \frac{w_1'}{W_1} \tag{47}$$

and from (**46**)

$$w_1' = 4\frac{W_1^3}{W_3^2} \tag{48}$$

substituting these values in (**35**)

$$w_1 = 2\,W_1\left(1 - 2\,\frac{W_1^2}{W_3^2}\right) \tag{49}$$

This condition of maximum efficiency generally differs from that of maximum output as defined in (**21**) unless $\frac{W_1}{W_3} = \frac{1}{2}$, as required by (**34**).

To show the effect of reactance on a line of constant resistance take F for the ratio of reactance to resistance.

$$F = \frac{X}{R} = \frac{W_2}{W_1} \tag{50}$$

The magnitude of the alternating constants W_1, W_2 and W_3 may be conveniently compared with the direct current constant W by taking the ratios $\frac{W_1}{W}$, $\frac{W_2}{W}$, $\frac{W_3}{W}$ which may be expressed in terms of F. This gives a relation true for any line, the alternating short circuit power and its two components being a fixed percentage of the direct current short circuit power for any given proportion of reactance. The relations from (**26**) are

$$\frac{W_1}{W}=\frac{W_1^2}{W_3^2}=\frac{W_1^2}{W_1^2+W_2^2}=\frac{1}{1+F^2} \qquad \textbf{(51)}$$

$$\frac{W_2}{W}=\frac{W_1\,W_2}{W_3^2}=\frac{W_1\,W_2}{W_1^2+W_2^2}=\frac{F}{1+F^2} \qquad \textbf{52}$$

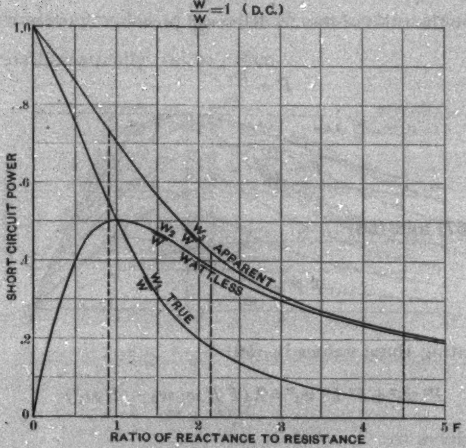

FIG. 6.—Short-circuit power

$$\frac{W_3}{W}=\frac{W_1}{W_3}=\frac{W_1}{\sqrt{W_1^2+W_2^2}}=\frac{1}{\sqrt{1+F^2}} \qquad \textbf{(53)}$$

These relations are plotted in Fig. 6 on which has been indicated the position of the constants of the No. 0000 line assumed above.

The maximum output for any given line reactance has been determined in (**21**); substituting the values from (**51**) and (**53**) gives

$$\frac{w_1}{W}=\frac{W_3}{W}-\frac{W_1}{W}=\frac{1}{\sqrt{1+F^2}}-\frac{1}{1+F^2} \qquad \textbf{(54)}$$

The relation between output and efficiency with different reactances may be determined for other than the maximum conditions already discussed as follows:
Transposing, squaring and adding (**35**) and (**36**) gives

$$w_3''^2 = w_3^2 + 2\, w_1\, w_1' - 2\, w_2\, w_2' + w_3'^2 \tag{55}$$

which with (**37**) gives

$$w_3'^2 = w_1'^2 + w_2'^2 = 2\,(w_2\, w_2' - w_1\, w_1') \tag{56}$$

Let P be the ratio of loss to delivered power

$$P = \frac{w_1'}{w_1} \tag{57}$$

Also

$$F = \frac{W_2}{W_1} = \frac{w_2'}{w_1'} \tag{58}$$

From (**57**) and (**58**)

$$F\, P = \frac{w_2'}{w_1} \tag{59}$$

Substituting these values in (**56**)

$$P^2\, w_1^2 + F^2\, P^2\, w_1^2 = 2\,(F\, P\, w_1\, w_2 - P\, w_1^2) \tag{60}$$

This reduces to

$$\frac{w_2}{w_1} = \frac{1}{2\,F}\,[2 + P\,(1 + F^2)] \tag{61}$$

Substituting from (**51**) and (**52**) in (**17**)

$$w_1^2 + w_2^2 = 2\left(w_2\,\frac{F}{1+F^2}\,W - w_1\,\frac{1}{1+F^2}\,W\right) \tag{62}$$

Or

$$\frac{w_1}{W}\left(1 + \frac{w_2^2}{w_1^2}\right) = \frac{2}{1+F^2}\left(\frac{w_2}{w_1}\,F - 1\right) \tag{63}$$

From (**61**)

$$\frac{w_1}{W}\left\{1+\frac{2+P\,(1+F^2)^2}{2\,F}\right\}=P \tag{64}$$

This reduces to:

$$\frac{w_1}{W}=\frac{4\,P\,F^2}{4\,F^2+[P(1+F^2)+2]^2}\ \text{or}\ \frac{4\,P\,F^2}{(2+P)^2\,(1+F^2)+P^2\,F^4} \tag{65}$$

The maximum value of $\frac{w_1}{W}$ with P constant may be determined mathematically to be when

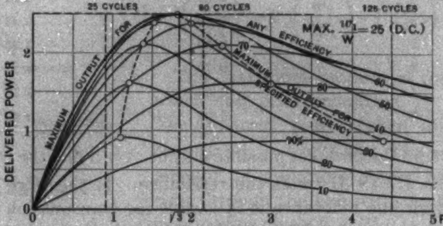

Fig. 7.—Delivered power

$$F^2=\frac{2+P}{P} \tag{66}$$

Substituting in (**65**) gives

$$\frac{w_1}{W}=\frac{P}{(1+P)^2}\ \text{or}\ 2\ \frac{F^2-1}{(F^2+1)^2} \tag{67}$$

The latter corresponding to the result for direct current checks the conclusion already reached.

In Fig. 7 the results of equation (**65**) are shown graphically, also the points of maximum output at given efficiency and maximum output at given reactance.

A line with no reactance will absorb a very large amount of power if short circuited but will transmit no power at constant potential. Give the line reactance and the power taken at short circuit is decreased but the line acquires the ability to transmit power. With increased reactance the short circuit power decreases continually, the ability to transmit power increases to a maximum and then decreases slowly. If the reactance is more than 1.73 times the resistance, the short-circuit power is actually less than the transmitted power as shown by Figs. 6 and 7 and the following table:

Line reactance	Short circuit power	Maximum transmitted power
F	$\frac{1}{1+F^2}$	$\frac{\sqrt{1+F^2}-1}{1+F^2}$
0	1.00	0.00
1	0.50	0.21
$\sqrt{3}$	0.25	0.25 (max.)
2	0.20	0.25–
3	0.10	0.22
4	0.06	0.18
∞	0.00	0.00

To obtain the greatest possible output over a line the reactance should be 1.7 ($\sqrt{3}$) times the resistance. It therefore appears that a high line reactance is favorable for transmission of large amounts of power by this system. Under short circuit, however, the line reactance greatly limits the amount of power that can be taken by the line. A short-circuited line may take less power than its full load. In other words, more power will flow into a line having no drop in voltage from generator to receiver than into one having full voltage at the generator and zero voltage at the receiver. On constant-potential systems of unlimited extent using high line reactance a short circuit would be a local matter, for one point may be short circuited without affecting the voltage except for a moderate radius and without concentrating any exceptional amount of power at the short circuit. Such a limitation on short circuits insures the continuity of the service as a whole, makes it safe to connect an unlimited amount of power to such a system (provided the sources are distributed) and sets a limit to the amount of power it is necessary to design switches to handle.

The same principle may be capable of further extension. Between large adjacent plants or between the two halves of a very large plant an artificial line of reactance without resistance may be introduced which will limit the power which may pass on short circuit without preventing the interchange of power required for ordinary multiple operation.

From this point of view the characteristics of constant-potential transmission of power over lines of zero resistance (that is through reactive coils)are of interest. Fig. 8. a modification of the previous one with $W_1=0$ shows the relation. Let W_2 be the apparent power taken by the line with one end short circuited. From **(17)** the power transmitted is

$$w_1^2+w_2^2=2\,w_2\,W_2 \qquad \textbf{(68)}$$

$$w_1^2=2\,w_2\,W_2-w_2^2 \qquad \textbf{(69)}$$

$$\text{or}\left(\frac{w_1}{W_2}\right)^2=2\left(\frac{w_2}{W_2}\right)-\left(\frac{w_2}{W_2}\right)^2 \qquad \textbf{(70)}$$

The maximum amount of true power which can be transmitted is $w_1=W_2$. The apparent power taken under this condition is $w_2=\sqrt{2}\,W_2$. The maximum amount of apparent power which can pass through the line with the two ends in opposite phase is 4 W_2.

Taking one-half the maximum as the normal rating of such a line it will at normal load take in addition at each end 27 per cent wattless power giving an apparent power of less than 104 per cent rating, that is a power factor of over 96 per cent, at the same time limiting the apparent power in case of a short circuit to 200 per cent rating or in the extreme case of the ends being out of synchronism and in opposite phase to 400 per cent of rating.

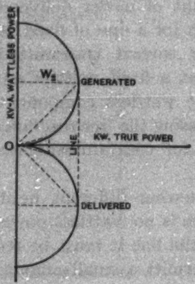

FIG. 8.—Power diagram —transmission through reactive coil

It has been shown that increased line reactance may actually increase the capacity of the line for transmitting power. The principle that line reactance is beneficial may be further extended by showing that adding reactance may also improve the efficiency of transmission. The greatest possible output over a line is obtained with a reactance 1.7 ($\sqrt{3}$) times the resistance but under these conditions the efficiency (as with direct current) is only 50 per cent. For commercial purposes the efficiency must usually be higher. Taking an efficiency of 90 per cent for example and referring to Fig. 7 it will be noted that with increased reactance an increased amount of power can be transmitted. The maximum being reached when the reactance is 4.4 ($\sqrt{19}$) times the reactance at which point the amount is as great as for direct-current transmission.

An equivalent result may be reached with Fig. 7 from a slightly different point of view by considering the transmission of a fixed amount of power say 1/10 of the direct current short circuit $\left(\frac{w_1}{W} = 0.10\right)$. From this it appears directly that increasing the line reactance improves the efficiency.

Improved efficiency for a fixed amount of power delivered must signify a decrease in line loss which for a line of fixed resistance can only be due to a smaller current transmitted. Since the working current is delivered at a fixed voltage any decrease in total current must be in the wattless component. It may be concluded therefore that increasing the line reactance decreases the wattless power necessary for constant-potential transmission.

Fig. 4 illustrates the point in a somewhat different light. It shows that for any line reactance there is no wattless power at no load. To get power to flow over the line it must be fed with wattless power; a small amount permits a small amount of power to flow, a larger amount of wattless power permits more and so on up to a certain maximum. It shows further that as before found for a given amount of power delivered increasing the reactance decreases the wattless power necessary.

Briefly, we may say that line reactance makes a line opaque to the natural flow of power, that is, for delivering power at unity power-factor or for absorbing it at short circuit. However by artificially introducing a suitable wattless current the line becomes transparent to the flow of power for the time being. Remove the wattless current and the line again becomes opaque. Short circuiting the line at the receiving end automatically removes the wattless current and decreases the flow of power. Furthermore increasing the line reactance makes the line more opaque to the natural flow and within certain limits more transparent to the artificial flow as facilitated by a given wattless current.

The phase relations in a constant potential transmission system of large extent are of importance. In the ordinary system of transmission by direct or alternating currents as the power flows the voltage decreases, in this system the voltage also undergoes a change but it is a retardation of phase not a reduction of magnitude. Phase retardation may be of unlimited magnitude thereby fitting the system for unlimited extension.

Take the simple case of a single generating station feeding a single transmission line with substations at intervals. Call the phase of the generating station *O* then that of the successive substations will be behind that of the generating station by amounts increasing progressively by regular or irregular intervals as for example according to the following assumed figures:

Generating station	*A*	phase	0	deg.
Substation	*B*	phase	− 60	deg.
"	*C*	"	− 120	"
"	*D*	"	− 180	"
"	*E*	"	− 240	"
"	*F*	"	− 300	"
"	*G*	"	− 360	"
"	*H*	"	− 405	"
"	*I*	"	− 450	"
"	*J*	"	− 495	"
"	*K*	"	− 540	"
"	*L*	"	− 570	"
"	*M*	"	− 630	"
"	*N*	"	− 690	"
"	*O*	"	− 750	"

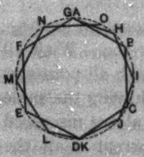

FIG. 9.—Voltage diagram of transmission lines

Fig. 9 is a vector diagram of the voltage phases of the several stations and the lines joining them. It is evident that the vector diagram is a polygon inscribed in a circle of radius equal to the nominal voltage. The polygon may be regular but will usually be irregular, it may be closed on itself but will usually be open either because incomplete or because the sides are not an exact submultiple of a complete circumference. If closed it may be so after one, two or more complete revolutions. The voltage at the stations are at the vertices, the sides representing the variation of the voltage along the line which it may be noted is always a minimum at the middle. The minimum being lower as the phase difference between consecutive stations increases. While the maximum difference in phase between any two stations on a system may be of unlimited amount that between consecutive stations is limited.

If the instantaneous voltages, instead of the vector voltages were taken they would show the potential moving forward in waves from *A* to *O*. From *A* to *G* would be one complete wave length, from *G* to *O* would be one and one-twelfth wave lengths. The frequency of the wave would be that of the voltage used, its velocity would be variable depending arbitrarily on the distances and phase difference between adjoining stations.

Referring again to the vector diagram; points of coincident phase such as *D* and *K* and *A* and *G* are of especial interest. Being of the same phase and voltage they may be connected and no current or power will flow over the connecting wire. If another line ran from *A* to *G* by a longer route and entered *G* with a phase of − 720 deg. then the two lines could be connected and (for the time being) no current would flow. It is analogous to connecting corresponding wires of two spiralled transmission lines, one with one and the other with two complete spirals.

Another case occurs where the phase retardation is not a multiple of 360 deg. but is a multiple of the phase angle of the system, that is of 120 deg. in a three-phase system or of 90 deg. in a two-phase system. Assuming that the system taken as an example is three phase and that another line runs from *A* to *E* and enters *E* with a retardation of only 120 deg. On testing out for phase it would appear that a phase of one circuit was in phase with *b* of the other and could be connected without flow of power or of current and similarly for the other two.

This phase relation would be stable only for a constant loading. As the load varies the phase relation will vary too. With all load off the natural condition of the system is with all points at phase *O*. Any interconnection between points having the same apparent but different actual phase relation as above discussed would cause the circulation of a short circuit current if all the load were taken off. However, once established, a system of indefinitely great extent while it would vary in load between certain limits would never return to a condition of zero load.

While it is possible and may be desirable to have a uniform potential over a network of reversible transmission lines, this condition is not essential. The fact that the potential may be higher at the receiving than at the generating end of a line has already been referred to. Stated generally the relative voltage at the two ends of the line does not determine and is not material as regards the direction of transfer of power. Therefore, in a network the relative voltage of the different junction points may be arbitrarily fixed at any reasonable percentage above or below the nominal voltage and held there without preventing the transfer of power. That is to say, on a 11,000 volt system some stations may operate at 11,000 volts exactly, others at fixed voltages of 10,000, 11,500 and 12,000 simultaneously without regard to variation of load or to the direction of power transfer. Lines with their ends held at different fixed voltages are reversible but not symmetrically reversible, neither is the substation equipment strictly interchangeable. In developing a system with a view to indefinite extension, complete interchangeability of apparatus, and perfect reversibility of transmission would point to uniformity of voltage as the logical plan of development. The equations given have therefore been limited to true constant potential transmission, though as here pointed out the principles on which such transmission depends does not preclude an established 13,200-volt system being directly interconnected (without transformers or auto-transformers) with another established 11,000-volt system, each continuing to operate at its own fixed voltage. There are, however, disadvantages to such a connection which make it desirable to avoid it where the differences of voltage are not yet established.

The formulæ given neglect electrostatic capacity and leakage. They are applicable to those cases where the voltage is not high or the length of section is not great. By modification they could be extended to include effects of capacity and leakage. It may, however, be noted that it is not the capacity of transmission system as a whole (which may be very great due to large extent) but the capacity of the individual line section which affects the accuracy of the calculation. In a preliminary examination of the theory of constant potential transmission it is advantageous to omit consideration of line capacity because while capacity may in certain cases greatly modify certain results, it is line inductance alone and not line capacity which is essential for producing the results. Although lines have capacity as well as inductance and although in a general way reactances due to capacity and those due to inductance are physical quantities which can cancel each other like positive and negative numbers, yet in a transmission line the capacity and inductance are related to the line in different ways (shunt and series respectively) and do not cancel but produce semi-independent results which are of a different nature. The capacity adds a component to the current, the inductance subtracts one from the voltage. In this method of transmission it is the inductive reactance which is of prime importance because that directly controls the voltage which it is the purpose to keep constant. The capacity reactance (or rather susceptance) of the system as a whole affects the amount of wattless current which it is necessary to produce at the several stations and substations, but as any amount necessary is supposed to be obtainable from suitable synchronous motors and generators, the capacity currents would be neutralized artificially whenever necessary at these points. On any section between two stations there would be a local effect which is however of only secondary importance.

DISCUSSION ON "ECONOMIC LIMITATIONS TO AGGREGATION OF POWER SYSTEMS", BOSTON, MASS., FEBRUARY 17, 1911.

A. E. Kennelly: The paper is of great interest, both theoretically and practically. It assumes the existence of not merely transmission system, but rather of a system of such systems; that is, it presupposes a network of transmission and absorption of power, including a plurality of generating and delivery stations.

In the ordinary transmission system of to-day, we are accustomed to regard the problem of electric pressure regulation as a corollary of the ordinary direct-current system. We expect to have a drop of pressure between the generating station and delivery station of not more than, say, 10 per cent of the delivery pressure, at rated load. This is a natural habit of thought derived from direct-current practice. In order to enable such a 10 per cent limit of drop to be maintained, the power-factor of the load may have to be restricted to a certain range, and condensive reactance may have to be supplied, with the aid of over-excited synchronous motors, in order to succeed.

If, however, a large number of transmisson and delivery lines spring up in any territory, it is evident that they must tend to coalesce; unless actually incompatible, so numerous and powerful are the engineering advantages to be gained by merging them into a single network. Having developed such a network, the complexity of maintaining assigned percentages of voltage drop on the lines, under various conditions of load, or of maintaining assigned percentages of power-factor, is likely to become excessive, and the old method of regarding the matter is therefore likely to become untenable.

The paper suggests that, under such conditions, much simpler conceptions and modes of operation are to be found in maintaining constant effective voltage at all station switchboards, and in ignoring the power-factors of the various loads, except in so far as these may indirectly have to be controlled in order to secure constant voltage. The idea is that no power-factor meters need appear on the various switchboards, and that the switchboard attendants shall regulate entirely for constant line-voltage.

In the paper reference is made to the fact that current may be made to flow in such a system from a point of lower to one of higher potential. This, of course, refers to effective, or r.m.s., potentials; because we know that, at any instant of time, current can only flow from a point of higher to a point of lower potential; but that, owing to difference of phase, the r.m.s. of the potential at the load may be greater than the r.m.s. of the potential at the generating point, taking the whole cycle of alternating potential into consideration.

We also know that all transmission lines necessarily possess magnetic reactance. If a lagging current flows over such a line, the drop of r.m.s. pressure, as between generator and substation switchboards, becomes exaggerated. If, on the contrary, every distinctly leading current flows, the drop of pressure may be negative, or the r.m.s. pressure may be higher at the substation switchboard. As an intermediate condition, if the current leads moderately, the apparent drop of pressure may be made zero, and the voltage at both switchboards will thus be the same.

The paper, therefore, calls for a system of inter-connected stations such that every load may be a suitable leading load. This means that adjustable condensive reactance must be supplied at each substation. It will not do to have mere non-inductive loads. A pure resistance load—a simple lighting load—or a load of 100 per cent power-factor, will not suffice. There must be a definite amount of lead in the load. The power-factor must be less than 100 per cent and leading, so as to produce neither rise nor fall of voltage at the substation switchboard. Consequently, a synchronous motor, of adjustable excitation, to act as a condenser, must be available at each substation where power is delivered. If the load is a purely lighting load, very little over-excitation will be needed in the synchronous motor of the substation, in order to maintain the required lead of current-phase, for constant line voltage at the switchboard. If, on the other hand, a heavy inductive load, is delivered, such as an induction-motor load, correspondingly powerful over-excitation will be needed in the synchronous motor. Variations of load will thus call for variations of excitation, to keep the switchboard voltage steady.

If there were no magnetic reactance in the line wires, the method here under discussion of reducing the apparent line-drop to zero could not be used. The paper points out that, up to a certain point, the presence of reactance in the line is useful, for the purpose of maintaining uniform switchboard voltages over the entire system. It is intimated, in fact, that extra reactance, introduced into the lines, may thus benefit power transmission. Loading a telephone line with artificial reactance is well known to be beneficial in the case of electric telephone transmission. The analogy at once suggests itself that if loading a line with reactance is beneficial in alternating-current telephony, the same plan may also be beneficial in alternating-current power-transmission. It must be remembered, however, that the effect of loading a telephone line is to increase its tension. It reduces the effective current and increases the effective voltage of transmission, and so reduces the $I^2 R$ losses, in essentially the same way that increasing the voltage improves the economy of power transmission. This is very different from the effect here considered of loading a transmission line, and there is no proper analogy between the two cases.

A suitable amount of magnetic reactance in the lines of a large power-network is likely indeed to be useful, as indicated in the paper, for limiting the violence of short-circuits, and the distance to which their injurious influences can extend; but it is questionable how far loading lines with reactance may be carried with advantage on other accounts. In a direct-current line of total resistance R ohms, a working current of I amperes will effect a drop of pressure of $I R$ volts, which must subtract from the generator voltage to give the substation voltage. In an alternating-current line of total impedance Z ohms, an effective working current of I amperes must similarly produce $I Z$ volts drop. The impedance Z must always exceed the ohmic resistance and may greatly exceed it if there is much reactance in the line. Now, as shown in the paper, it is possible to swing the $I Z$ drop into such phase relation to the generator-end voltage, that the vector difference, or receiving station voltage, may be numerically equal to the generator end voltage; but the greater the $I Z$ drop, the greater will be the changes of voltage that variations of load will tend to effect; or, to express the same condition in another way, the closer and more cared for will be the adjustment of leading current and condensive reactance that the synchronous motor must produce. Moreover, the greater the reactance in the system, the more powerful the surge overvoltage in the system that a given disturbance will set up. Consequently, the principle of the benefit derivable from extra reactance in such a system should be received with caution.

The author of the paper is to be complimented upon the very interesting and beautiful geometrical theorems which he presents in the supplement. These theorems are restricted to the limitation, laid down as a postulate, that constant voltage is maintained at the stations on the line. If this condition is departed from a considerable deviation may be involved in the conclusions. in some practical cases. But, from a theoretical standpoint, and within this limitation, the results deduced are very interesting.

It is to be regretted that in a paper which bids fair to be long remembered, the term "wattless power" is employed. This criticism is directed solely to language used, and not to the facts which the language is intended to express. The term "reactive power" would be just as easily understood, and would give rise to no self-contradiction in terms, besides avoiding ambiguity. Reactive volt-amperes in an alternating current system are just as "wattful" as the volt-amperes that are delivered and recorded through time, on the watt-hour meters; except that the reactive power is developed in displacing energy within the system from one part of the system to another; while the delivered power is developed in displacing energy from inside the system to the consumer's apparatus outside the system. Delivered power is saleable, and reactive power is not saleable; but the commercial distinction should not interfere with the terms and concepts of the matter, as they are reflected in the mind of the engineer.

N. T. Wilcox: The cheapening of hydraulic development due to the lesser cost and large production of Portland cement and the ability to transmit successfully at voltages of 100,000 or more have made things possible to-day that were impossible a few years ago. We even hear rumors of higher voltages than those mentioned.

It seems to me of prime importance that in the development of these propositions, efficient and competent engineering talent be employed. If these large plants are developed along wrong engineering lines, the resultant mistakes crystallize as a permanent tax on the whole development. We may be able to get rid of bad management, but are seldom able to get rid of the charges following a badly engineered development.

E. A. Ekern: The constant potential system as outlined in the paper by Mr. Philip is an ideal system as regards voltage regulation. To obtain this ideal voltage regulation it presupposes a sufficient and ample control of the power factor of the load at all of the various points on a transmission system.

With the continued growth of the high-tension transmission systems has developed a continual battle on the part of the engineers operating these systems to maintain a reasonable power factor which is essential to good voltage regulation. Until recently the tendency has been to attempt to improve the regulation by increasing the voltage. Except for the larger systems distributing large quantities of power to central points a limitation to the increase of voltage has been found in the corona loss from the small sizes of conductor and in the operating difficulty of charging the high tension lines which require a very large charging current and consequently a large current carrying capacity in the generating stations. In spite of the increased voltage of transmission of some of the long distance transmission systems until they are operating under the above conditions of corona loss and large charging currents many are experiencing difficulty in obtaining good voltage regulation on account of the low power factor resulting from the extensive use of the induction motor which predominates the field of small individual drive.

Many transmission engineers are turning their attention from the problem of increasing the voltage which has been solved quite satisfactorily and appears to have reached its present limitation for smaller systems, and are devoting their energies to improving the power factor and devising an equitable basis of charging for energy depending on the power factor of the load and its influence on the transmission system. This is being done to such an extent that it is now quite common practice to charge additional for energy of a load having a lagging power factor and placing a premium on energy of a load having a leading power factor. An excellent system for a rational basis of compensation according to the character of load was outlined by Professor Hooper at the last meeting of the Boston Section held at Tufts College. This system consisted of not only metering and charging for the kw-hr. of energy but also metering and charging for the kw-hr. of wattless energy according as to whether it is lagging or leading.

If a system can be obtained which places a premium on a satisfactory power factor so that it will be found desirable to control the power factor at the various points of loading a high-tension transmission system it becomes quite possible to obtain the conditions as outlined in Mr. Philip's paper and the constant potential system will then be realized.

Edw. N. Lake: Two or three of the preceding speakers have appeared to be of the opinion that the paper this evening applies particularly to electrification problems. It seems to me that it has a very much broader application than the electrification of steam railroads. It involves, to my mind, all of the uses to which power may be applied and is a most daring conception—that of a high tension network covering the whole country just as a 250-volt or a 600-volt network serves a very limited territory.

Electrification of steam railways will never become general until two of the fundamental ideas of Mr. Philip's paper can be commercially applied; *viz.*, uniformity and interconnection. Transposing into railway language, uniformity becomes standardization, interconnection corresponds to interchange. Electrification cannot be made attractive to the railway man until standardization and interchange are positively assured to him.

R. P. Jackson: Mr. Philip's paper outlines a system of power transmission or rather of power traffic which is of unusual interest. The possibility of many or all power producers and users pooling their interests and supplying power to a common fund or drawing from this fund as it were, to meet their immediate needs is in the nature of a banking operation with electric power taking the place of funds.

One point of note, however, is that while *watts* may be the commodity exchanged the medium of exchange must properly be *voltamperes*.

While a customer who fails to supply his own lagging current may be automatically penalized by a drop in his supply voltage, yet his load may be such as not to suffer greatly from this cause while another customer adjacent in line connection may be inconvenienced by such drop. There is, moreover, to be considered the effect on generator capacity.

Consequently the system of metering must either register in volt-ampere-hours or preferably in two separate records, one of true power and the other of wattless ampere-hours. This would permit a system of premiums and discounts to be used, taking into account the quality of the medium of exchange.

According to the method of regulation given by Mr. Philip a more equitable system of metering might be to measure the power and the integrated volt-seconds of variation up or down from a standard line voltage.

Then either a power producer or a power user could be penalized for variations from the voltage of the system.

Metering devices to accomplish these results, however, are not now available so far as we are aware. Metering problems are even now rendered difficult by the question of maximum demand and limitation of peak loads, and the introduction of the necessity of taking account of apparent watts still further complicates the matter. The other advantages of the system described by Mr. Philip are such, however, that, should the commercial application of it demand, suitable metering methods and devices would doubtless be forth-coming.

Another feature of interest is that line reactance is no longer a disadvantage but on the other hand becomes a necessity. It is even suggested that artificial reactance in the form of choke coils be inserted in series with the line for the purpose of giving the greatest power carrying capacity to the line. Substantial choke coils such as are often used to protect against lightning and similar high frequency oscillations could then serve two purposes and cease to be looked upon with suspicion on account of the drop incurred.

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COMMENTS ON FIXED COSTS IN INDUSTRIAL POWER PLANTS

BY JOHN C. PARKER

Certain features of the cost of power generation in small plants seem to be the subject of such varying ideas that it has been thought worth while to indicate a few of these features with the hope that a discussion of them may bring about a greater consistency of view among the members of the profession. The features presented in this paper will for the most part be confined to "fixed costs," comprehending thereunder those costs which are not closely a function of the energy output. While the latter elements of cost are more or less obvious during plant operation, the fixed costs are capable of but little modification or correction after a plant has been installed, and being a matter of economic rather than of technical judgment, and hence not always attracting the attention of engineers who may not have specialized in economic essentials, it is at once desirable that attention be called to them, and that they be given considerable weight during plant layout. The writer would call particular attention to the marginal principal discussed in the latter part of this paper as being one of critical importance, and one of those least commonly weighed by the profession.

Investment. As most of the fixed costs have to do with the *investment* made in the plant, it is worth while to call attention to a few of the component items of the investment. It is, of course, obvious that the purchase price of the machinery must be included. The writer has been surprised, however, to note in dealing with something over 300 industrial engineering propositions, that in many cases the preliminary estimate of the plant investment will stop at this point without giving consideration to the cost of real estate, housing, to freightage and teaming, sometimes without attention to the labor involved in installation. Supervision is very often entirely overlooked, and yet engineering design and supervision are just as much a part of the cost of a plant as is the engineering design that is paid for when the purchaser lays down the purchase price for an engine or for a generator. It might seem superfluous to mention this almost obvious fact, did not the writer recall that in a recent consultation with a public service commission objection was made to carrying depreciation on the labor and superintendence involved in setting transmission poles, placing station machinery, *et cetera.*

Since the installation of a plant costing $10,000 or $20,000 will constitute a physical improvement to the property, it is obvious that the *tax* assessment will be increased thereby, and that this fact should be reckoned on in pre-estimating power cost. It is unnecessary, of course, to more than mention this fact in the way of a memorandum.

Insurance. The cost of carrying *insurance* is sometimes overlooked in pre-estimating power cost. It is obvious that this is just as much a part of the cost as coal and superintendence. It may not, however, be quite so obvious at first blush that something more than the insurance on the plant investment may have to be assessed against the plant, but on slight reflection this will be seen to be a possible, and in some cases, a very certain condition. If, for instance, the installation of a plant increases the fire hazard on the property as a whole, the net increase of insurance on the property should be assessed against the plant which has occasioned this net increase. In addition to the ordinary fire insurance there must be carried, in some form or other, accident and liability insurance, and this will vary with the nature of the industry for which the plant is installed. In a manufacturing plant the possibility of accident to plant employees only would have to be considered, whereas in a department store the patrons of the store would have to be covered as well. This expense and the fire insurance are existent whether such insurance is actually carried, or not, since a sum of the same order of magnitude as the insurance premiums must be laid aside to provide for such contingencies for which the insurance is carried.

Interest. The writer has found very few cases in which *interest* has not been considered in some form or other, but in general he has found that not only the *engineers*, but the business men contemplating the plant installation—a class from which one might expect deep appreciation of such details—habitually underestimate the cost of borrowing money. Many details other than the merely nominal interest rate enter here, a fact readily recognized by any concern that has occasion to float bonds or preferred stock; and these details should, of course, be given their due weight in each case in determining what interest burden a plant will have to bear.

It is worth noting that very few business concerns have an unlimited borrowing capacity, in fact, any prosperous and extending business may be expected to closely approximate its credit limit, so that a further extension of obligations will definitely depreciate the total credit of the concern for borrowing purposes, thereby either hampering the borrowing of money or increasing the interest rate that must be paid. In such a case the part of the business so prejudicing the borrowing capacity should be compelled to carry the burden thereof itself, rather than to distribute the burden over the business as a whole, since this part of the business is responsible for and occasions the additional expense. For a fuller discussion of the principle underlying this, reference may be made to the already mentioned marginal principle appended to this paper.

Depreciation is the subject of as widely variant views as exist in any of the details of plant cost. The writer has found that in many cases the life of a plant will be estimated from the length of time that some plants have been in service. This seems to be an utterly untenable basis for calculation, since many an engine may be found to be operating at the end of 30 years from its initial installation without the fact of necessity proving that the depreciation rate should properly have been assumed as 3⅓ per cent; it might be that the plant should have been scrapped 15 years previously. The desirable and proper life to assume for a plant is the length of time for which it can in all probability be *economically* run; in other words, depreciation should be predicated on the date at which the plant *should be* put out of commission, rather than the date at which plants *have been* put out of commission as a result of absolute failure to functionate. The time at which scrapping of any apparatus in any given plant should occur is that at which the reduced efficiency and the increased maintenance, renewal, and repair costs of that detail are great enough to justify the purchase of new apparatus under the particular operating and business conditions obtaining.

It seems highly objectionable to take an average rate of depreciation and apply it to the power plant as a whole. The depreciation rate is considerably greater on boilers than it is on engines; considerably greater on engines than it is on buildings, and so on. If, then, a plant has a preponderance of those items which will deteriorate rapidly, the depreciation rate will be high, and *vice versa*. Each class of apparatus and construction in the plant should be multiplied by its own depreciation rate, and the aggregate of the products taken as the depreciation expense per year. This is not a particularly arduous task, since the apparatus will naturally group itself into a very small number of general classes.

An over estimation of depreciation rates should be guarded against, of course, and for this purpose a sum should be set aside each year, which, with the compound interest that it can earn, will at the end of the life of the various classes of apparatus in the plant pay for their replacement. On short life apparatus this is not an item of so much importance as it is on the classes of longer life. The propriety of so figuring amortization, irrespective of whether a proper sinking fund is allowed or not, is determined from the fact that if such sinking fund deposits are not made, the money that would have gone into them appears as a part of the earnings of the firm, and is paid out immediately to the stockholders, who thereby have the use of the money which, however employed, should earn the same compound interest as would be earned by the money if placed in a sinking fund.

In this discussion of depreciation no attempt is made to indicate where maintenance, renewals, and repairs should cease, and depreciation begin. It is for each engineer to determine for himself how far he can afford to go in making these operating expenses avert the day when a plant will have to be scrapped. Once having determined the most economical relation between these operating expenses and the proper life to assume for the plant, both they and the amortization fund should be included in the pre-estimate of the power cost.

Obsolescence. If by this term we mean the supersession of the apparatus initially installed by a more efficient type which may develop before the initial apparatus has reached the scrapping point, it is not an important charge, even though the supersession may take place under stress of competition, since such supersession will not be undertaken unless the new apparatus can save enough to justify the expense, in which case these savings must themselves take care of so much of the new investment as is not already covered by the sinking fund which should have been provided by the old plant. Obsolescence, therefore, has essentially no existence for private power plants even under stress of competition.

The case is somewhat different where the business of a concern is power sale. In this case the "quality of power," as well as the cost of its production, is a vital element in competition, so that the development of a new type of apparatus which will improve the quality of the power supply may render existing machinery obsolete, and under stress of competition from privately owned plants, or from a competing utility company, may force supersession, as, for instance, the development of 60-cycle apparatus forced many of the higher-frequency generators out of commission before the termination of their natural life.

In one respect it may be desirable to carry an obsolesence fund even in an industrial plant. The existence of such a fund renders more readily possible the supersession of the obsolete apparatus when economically justified—it has in fact the effect of rendering fluid the plant investment at the expense of the earlier years of operation before obsolescence may arise, and when the stress of competition may be less burdensome. The managers of the industry must themselves consider how much weight they will give to this consideration by attempting to prognosticate their future borrowing capacity for supersession purposes.

In case of the supplanting of a private plant by a public service supply, or of one private plant by another, the new plant will have to carry its own depreciation burden, and in addition, the portion of the older investment which has not already been provided for. The convenient way of considering this is to calculate what the sinking fund on the old plant should have amounted to on the date of supersession, and to credit the new equipment with this, and to then compel the new equipment to carry the burden of the old throughout the life of the new equipment, together with its own proper depreciation burden.

Supervision falls under the "marginal" principle referred to above. Briefly stated, this principle is that, if any part of a business requires time, material, or investment which could have been utilized in any other part of the business, the cost thereof should be taken as what such time, material, or investment would have earned if applied to the most profitable part of the business which is still capable of extension. If, for instance, a power plant requires during installation, regular operation, in accounting, and during period of disability, 20 per cent of the time of the manager of the industry; and if the time of the manager expended in works supervision, supervision of sales, or any other detail proper to the industry, would increase the profits of the concern at the rate of $10,000 per annum, it is proper to charge the power plant with $2,000 a year for supervision.

In general the magnitude of power generation by a factory plant is not great enough to make it possible to employ or to attract a $2,000 a year man to supervise the plant operation, and yet many such plants actually deflect from the earnings of the industry by the distraction of the manager's attention a sum considerably in excess of such an amount. Failure to properly weigh this principle at the inception of the power plant installation may materially hamper the operation of the firm. It may be said that this principle presupposes capacity for extension in the various activities of the concern, which capacity may not be realized in fact, but it is pretty generally the case that a man who is fit to be at the head of any manufacturing or mercantile enterprise is about the busiest man in the concern, and that he has not any excess of leisure for devotion to the legitimate business of the concern. It is almost impossible to conceive any business incapable of extension by proper commercial attention to the discovery of new avenues for the output by proper advertising skill, or incapable of improvement in production processes by skilled attention directed to the processes of the enterprise.

Fair Profit. No man running a department store would think of putting extra capital into the china department where, in the nature of things, the turnover is small and the profits limited, if the clothing department, with a turnover of the stock thirty times per year, was not carrying a maximum business obtainable. Such a merchant would study his business and place each thousand dollars where it would earn the greatest profit, and would figure that the deflection of $1,000 from a department that could earn $300 per year, to a department that could earn only $100 per year, had actually cost him in the loss of profits $200 per annum. This is a tacit recognition of the marginal principle. If, then, an enterprise is making a net profit of 10 per cent per annum on the average—and not less and probably more than this on certain details of the business—there is manifestly at least a 10 per cent per annum loss in the investment of money in a power plant—or in any other part of the business—if the money earns only the fixed items of taxes, insurance, interest, depreciation, and supervision, and the amount lost is just what could have been gained by the investment of such a sum in the most profitable part of the business. How much this shall be must be determined for each individual plant, but for the sake of fixing an idea of magnitude the writer would say that he recently encountered two instances in which the proprietor of an establishment figured, as a proper charge against his contemplated power plant, at least 10 per cent of the initial investment to cover "fair profit."

It is, of course, obvious that if the business is not capable of further extension, and if the investor knows of no such other business, or if the credit of the business is so good as to render it possible to borrow without difficulty enough funds to take care of all possible extensions, and to still have enough to install a power plant, the plant would not have to carry a more than nominal fair profit burden. Such a condition, however, is not at all a usual one, and will, therefore, have to be reckoned with in but few cases.

Building space and real estate come under the same marginal principle. It is not uncommon to hear the statement made that there is a certain amount of space that is wasted anyhow, and that might as well be used for power plant. The statement is correct where injudicious over-purchase has been made, or where excessive purchase has been compelled in order to secure what land was desired. But, with this one exception aside, it is not at all proper to underestimate the rental value of the space. In the case of a mercantile establishment, for instance, the basement space is often used for boiler and engine plant room. This is permissible if there is no other use to which this space can be put, but it must be remembered that if this space is rendered useless for storage purposes, storage must be effected in the least desirable part of the establishment then remaining, thereby cramping such space and perhaps forcing an overflow into still more desirable space. The fair rental value must therefore be assessed as part of the annual cost of maintaining the power plant.

APPENDIX A

The marginal principle is much broader in its application than the subject matter of this paper, bearing as it does not only on matters of economics, but on many more strictly technical matters. The writer has found many cases where average or mean figures have been used in discussing various phenomena, and where conclusions arising from such use of averages were practically meaningless, yet not positively invalid.

For example, it may have been determined that refinements may be introduced into the construction of a hydroelectric plant whereby its capacity may be extended, and the degree of such extension may have been fixed on the assumption that it is worth while to spend, say, $150 per horse power for the development. A not uncommon practice is to design a plant with such refinements up to the point where the average cost per horsepower is $150. As a matter of fact, this would result in an over-development of the refinements, as will be seen in the sequel.

On a little consideration of our example it will be clear that the first horse power developed would reach a very high figure, indeed; that thereafter, capacity might be developed at progressively lower cost per horse power, especially if the development were concentrated in few units, but that a point will be reached where, owing to the difficulty of securing additional capacity through storage, enlarged pipe lines, more expensive turbines, *et cetera*, the cost per horse power will again increase. It is clear that if the average cost per horse power is only $150, and the cost of the first few horse power developed considerably greater than this, the cost of a certain part of the capacity must have been below the average figure of $150. It is further clear that the increasing cost of capacity at the point at which development is stopped of necessity entails a cost per unit greater than the average figure, so that the cost of such a unit at the point of termination of development will be above the average, and that such a unit is therefore a disadvantageous one to add. With this illustration we pass to a general discussion of the marginal principle.

The margin may be defined as the point at which development of an enterprise or of a physical construction is stopped. As a matter of economic expedience, the last unit of development added, that is, the unit existing at the margin, is called the marginal unit; and for a proper appreciation of the proper point at which development should cease, we must look to the marginal unit and determine whether the cost of, or the advantage from this unit justifies its undertaking. It is unfair to the marginal unit, and economically fallacious to load onto it the burden of the disadvantageous initial unit on the one hand, or to credit it with the virtues of the intermediate units on the other.

Referring to Fig. 1, where, for example, we have plotted the investment in an enterprise as abscissæ, and the profit from such an investment as the ordinates, we observe that by projecting the curve back to zero investment, we have a condition where negative profits would ensue, that is, initially the business is a losing concern, since, with no business whatever transacted, the cost of operation constitutes a total loss. As the business

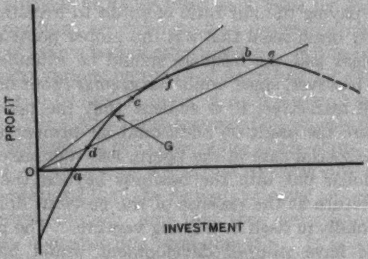

FIG. 1

develops, income begins to accrue and the loss is minimized. At the point *a* the volume of business and the investment therein have reached such a point that the business is no longer a losing venture, as the term is ordinarily accepted, but it is making no return over the interest, depreciation, and other such obligations. Beyond this point profits steadily increase to a point *b*, where, owing to any one of many possible conditions, such as over-saturation of the market, and the consequent reduction in selling price, or to the organization having become top-heavy, the total profits no longer increase. Beyond this point a decline in profits obtains. The point *c* of tangency of a straight line drawn through the origin is the point of maximum ratio between profit and investment, but this point is not of necessity the point at which extension of business should cease, any more than is *b* the point of maximum aggregate profit. Drawing line *O e*, the tangent of whose angle of slope represents the fair business profit with which the promoter of the enterprise would be satisfied, we note that it has two intersections with the curve, one *d*, the other, *e*. It is manifest that the curve might lie so low as to be tangent to this line, or actually drop below it. In the latter case the business would not be attractive as an undertaking since the promoter can find more satisfactory investment for his capital. If, however, the curve intersects the fair profit line in two points, such as *a* and *e*, these points mark limits within which the business can be carried on without being undesirable as a whole. The slope of any line drawn from the origin to any point *G* between *d* and *e* represents the average profit per dollar invested when the business has been carried to the point *G*. It is manifest that if the point *G* is moved up to *e* the business will still be paying the fair ratio of profit to investment, and it might at first blush seem that *e* is the proper point up to which the investment and the business should be extended. This is not correct, however, since, while the *average* profit of the investment is still attractive, it is evident that the point has been reached where the profit on additional investment is very low, or, as in the special case in the figure, less than zero; that is to say, each dollar put into the business beyond the point *b* is making its return at the expense of the previous dollars put in, and may actually in itself be a losing venture. The proper point at which to have stopped development would have been *f*, the point of tangency of a line drawn parallel to *O d*, since up to *f* each dollar put into the business has been earning more than the fair business profit. At *f* only the fair business profit is earned; beyond this point less than the fair business profit is earned on each dollar invested.

From the above we see that the highest ratio of total profit to total investment obtained at the point *c*, but that the extension of the business should not have been stopped here; and again that it would not be advantageous to extend the business to the point *e*, where the ratio of total profits to total investment—in other words, the average return— is yet above the fair profit with which the promoter will be content; but that the point at which to stop development is that where the marginal investment produces a marginal profit of not less than the fair profit which will satisfy the promoter. Mathematically expressed, this means that the first derivative of the profit with respect to the investment must equal the fair profit ratio.

Specific applications of this principle have been referred to in the body of the paper in considering the liability and fire insurance cost due to the adding of a local power plant to an enterprise, in which case the local power plant constitutes the marginal investment, and where we are concerned with a cost function rather than with a profit function. A similar marginal investigation must be made in the case of the interest cost involved in the addition of a power plant to the concern, rather than a consideration of the average rate of interest, which will have to be borne by the enterprise after the power plant is installed. As previously pointed out, the applications of the marginal principle are various and have to do as well with the technique as with the economics of engineering effort.

APPENDIX B

For the purpose of fixing ideas as a basis for discussion, the following equations are submitted as representative of a group of methods of taking care of amortization. It is to be understood that there are various methods of providing for this fund, and that much is to be said in favor of each one as contrasted with the others. The method here presented distributes the amortization uniformly over all the years of life of the plant, but is not of necessity an expression of the actual physical rate of deterioration. It is assumed that the deposits into the amortization fund are made semi-annually, and that they draw interest at a fair market rate, compounding semi-annually. It is assumed that the amortization funds are invested where the risk, both physical and financial, will be the same as in the investment covered.

Let $\frac{a}{2}$ = semi-annual amortization rate.

$\frac{i}{2}$ = semi-annual interest rate on amortization fund.

n = number of years of life.

P = principal sum invested.

At end of first half year there will be deposited in amortization fund $P\frac{a}{2}$

which at the end of the rth year will have compounded to

$$P_1 = P\frac{a}{2}\left(1+\frac{i}{2}\right)^{2r-1}$$

and the second semi-annual deposit to

$$P_2=P\,\frac{a}{2}\quad \left. 1+\frac{i}{2}\right)^{2r-2}$$

There will have been $2r$ such deposits of total amount

$$\sum_1^{2r} P_q=P\,\frac{a}{2}\;\left\{\left(1+\frac{i}{2}\right)^{2r-1}+\left(1+\frac{i}{2}\right)^{2r-2}+\;.\;\;.\;\;.\;\;\left. 1+\frac{i}{2}\right)+1\right\}$$

$$=P\,\frac{a}{2}\,\frac{\left(1+\frac{i}{2}\right)^{2r}-1}{\frac{i}{2}} \tag{1}$$

When $r=n$; that is, at the end of life we should have

$$P=\sum_1^{2n} P_q=P\,\frac{a}{2}\,\frac{\left(1+\frac{i}{2}\right)^{2n}-1}{\frac{i}{2}};$$

$$a=\frac{i}{\left(1+\frac{i}{2}\right)^{2n}-1} \tag{2}$$

Substituting this in (**1**) we have

$$\sum_1^{2r} P_q=P\,\frac{\left(1+\frac{i}{2}\right)^{2r}-1}{\left(1+\frac{i}{2}\right)^{2n}-1} \tag{3}$$

the amount of the amortization fund.

The unamortized part of the principal sum then is

$$P-\sum_1^{2r} P_q=P\,\frac{\left(1+\frac{i}{2}\right)^{2n}-\left(1+\frac{i}{2}\right)^{2r}}{\left(1+\frac{i}{2}\right)^{2n}-1} \tag{4}$$

Equation (**1**) above gives the accumulated amount of the amortization fund at any time during the life of the plant. Equation (**2**) gives the method of arriving at the annual amortization rate. This must be determined to substitute in equation (**1**) for its solution. Equation (**4**) gives the net burden that would have to be carried by any new installation in case of the supersession of an older one.

These equations in the case of any numerical calculation become much simpler than they appear in the literal notation; for example, in the case of a plant of 20 years' life, the amortization fund for which draws interest at the rate of 6 per cent per annum, equation (**2**) would become

$$a = \frac{0.06}{1.03^{40} - 1} \tag{5}$$

and equation (**1**) at the end of 7.5 years takes the form

$$\sum = P \frac{a}{2} \frac{1.03^{15} - 1}{0.03} \tag{6}$$

and equation (**4**) gives the unamortized debt as

$$P \frac{1.03^{40} - 1.03^{15}}{1.03^{40} - 1} \tag{7}$$

APPENDIX C

As an illustration of the operation of a few of the principles laid down above, the author appends figures presented to and endorsed by the owner and manager of a large mercantile establishment. The plant contemplated was to aggregate 150 kw. of generating capacity, divided between a 100-kw. and a 50-kw. direct current generator. The figures used are in large part based on the manufacturer's quotations and guarantees, and for the remainder, on experience derived from investigation of something over 300 small industrial plants, and are felt to fairly represent average conditions in plants of this character.

Table 1 shows the distributed costs, and the method of arriving at the amortization rate. Building and real estate are not included, since the plant was to be installed as a basement plant, the fair rental value of which is assigned in a later tabulation.

TABLE I

Item	Cost	Life	Amortisation	
			Rate	Amount
		years	per cent	
Engines	$4,195	20	2.67	$112.00
Boilers, stokers and breeching	6,200	20	2.67	165.54
Stack	1,000	30	1.23	12.30
Generators and switchboard	4,700	25	1.78	83.66
Boiler auxiliaries	620	12	5.82	36.08
Piping	2,150	20	2.67	57.40
Foundations	300	20	2.67	8.01
Coal hoist	600	10	7.45	44.70
Aggregate	$19,765			$519.70
Mean			2.63	
Freight and rigging	500		2.63	13.15
Total	$20,265			$532.85

The marginal interest was assumed at 6 per cent. This is undoubtedly low for the specific case in point, since the enterprise was already limited in its borrowing capacity. The plant owner approved the fair profit ratio as being the minimum with which he would be content.

TABLE II

Marginal interest	6.00	per cent
Amortization	2.63	
Taxes and insurance	3.00	
Fair profit ratio	11.50	
Aggregate	23.13	per cent

Careful calculation of the heating requirements of the building were made, basing them on the usual commercial operation of the heating systems in buildings of this nature.

As another illustration, the following figures derived from actual operation of a 120-h.p., four-cycle, two-cylinder, horizontal, single-acting, 200-rev. per min. gas engine and suction producer plant are presented. The fuel and water consumption may appear high; it is noted, however, that these figures are derived from the actual total consumption during six months commercial operation, and that the kilowatt-hours are the actual record by the switchboard meters of the net kilowatt-hours usefully delivered to the plant. Were the figures given in terms of indicated horse power-hours, they would have been materially lower, as a result of the elimination of energy required to operate auxiliaries. It is to be noted that in the balance sheet coal, water, and labor for heating the plant, and labor, supplies, and

TABLE III

.........COMPANY

BALANCE SHEET

R. R. & L. Co. Electric Service-Heating from ...... Company Boilers

*Coal**

For heating. Based on 10 lb. evaporation. Day coal................280 tons

Night coal..............231 "

Banking coal........... 20 "

Total...............531 "

Cost @ $2.60.................$1380

Ashes

Ash, 12 per cent. Total ashes 64 tons removal cost @ 25c. per ton.......................... 16

Labor

1 fireman 52 weeks @ $15..$780

1 " 20 " @ $15.. 300

1080

Supplies and Repairs

$0.794 per h.p. per year 200 h.p. installed.................... 160

Water

Assume 10 per cent loss in system cost @ $0.012 per 1000 lb....... 12

Electric Service

Present maximum demand....107 kw.

Estimated future maximum demand........................140 kw.

The maximum and kw-hr. used each month for the past year have been increased by the ratio of 140 to 107

Estimated cost

Month	Kw-hr. 107–140	With discount
June	15980	$493
July	14850	365
Aug.	15270	399
Sept.	12540	401
Oct.	20820	535
Nov.	27450	610
Dec.	32800	655
Jan.	27420	605
Feb.	25230	581
Mar.	20720	541
Apl.	20700	540
May	19530	534
	253310	$6259

Total...................... 6259

Elevator Service

Present installation, estimated cost.......................... 415

Fixed Charges

Estimated value of heating plant $3,200

Fixed charges @ 25 per cent... 800

Manager's Time

And clerical expense.......... 25

Credit to Balance............ 2816

Total..................$12,963

*Best possible practice, purposely assumed conservatively.

Isolated plant

Fuel

253,000 kw-hr. @ 6.5 lb. coal 823 tons

Banking coal................ 58 "

Total...................881 "

Cost @ $2.60 per ton........... $2290

Ashes

Ash, 12 per cent. Total ashes 100 tons. Removal cost @ 25c. per ton...................... 25

Labor

1 day engineer @ $21 per week

1 night " $17.50 "

1 fireman $15 "

Total...........$53.50 "

All labor on for 52 weeks

Total cost per year............. $2780

Supplies and Repairs

Cost per year per boiler-h.p. installed $1.22. Cost of 300 h.p... 366

Water

10 per cent loss during winter, and exhaust wasted during summer

Cost per year.................. 60

Emergency Service

At 250,000 kw-hr. per year, av. per day is 800, av. per hour 33.

Assume 4 days shut-down per month, at ⅓ load or 11 kw. for 100 hr., a total of 1100 kw-hr. Assume max. demand at twice the average.

$$\text{Hours use } \frac{1100}{22 \times 26} = 1.9$$

Rate 7.1 cents.

Cost per month.................. $78

" " year.................... 936

Elevator Service

Present installation, estimated cost.......................... 415

Fixed Charges

Estimated cost of plant $19,200

Fixed charges @ 23.13 per cent. 4,441

Manager's Time

½ hour daily of 6-hour day @ $12,000 per year................ 1,000

Clerical expense, 1 hour daily, 300 days per year @ 50c........ 150

Rental Value of Space

500 sq. ft. @ $1.00 sq. ft...... 500

$12,963

fixed charges on the motor-drive are carried at zero, since it so happens that all these charges were carried as separate charges in the actual case of the gas engine plant, and they have, therefore, been eliminated from both sides of the balance sheet. Table IV represents the fixed charges, and Table V the balance sheet for this special plant.

TABLE IV

Investment in engine, generator, producer, switchboard, auxiliaries, and building, $11,000.

Average life (above), 12 years	
Amortization rate	5.81 per cent (6 per cent compounded semi-annually)
Marginal interest	6.00
Taxes and insurance	3.00
Fair profit ratio	10.19
	25.00 per cent

TABLE V
BALANCE SHEET

R. R. and L. Co. Electric Service		Isolated plant	
Coal		*Coal* 119,200 kw-hr. @ 4.6 lb. coal per kw-hr. =275 tons @ $3.10	$852.00
Water		*Water* 119,200 kw-hr. @ 27.2 gal. per kw-hr. =434,000 cu. ft. @ $0.98 per 1000	425.00
Labor		*Labor* One engineer, 52 weeks, @ $22	1,144.00
		Helper, 2 hours per day, 150 days =300 hours @ $0.30	90.00
Supplies		*Supplies* Oil, waste and supplies	265.00
Electric Service		*Emergency Service*	

Month	Kw-hr.	Net Bill		Month	Kw-hr.	Net bill	
Jan.	11,860	$315		Jan.	2141	$150.73	
Feb.	11,860	315		Feb.	1263	95.99	
Mar.	9,320	266		Mar.	211	20.00	
Apr.	9,320	266		Apr.	55	20.00	
May	7,920	247		May	124	20.00	
June	7,920	247		June	258	20.64	
July	9,320	266		July	260	20.80	
Aug.	9,320	266		Aug.	206	20.00	
Sept.	9,320	266		Sept.	286	22.88	
Oct.	9,320	266		Oct.	149	20.00	
Nov.	11,860	315		Nov.	732	58.56	
Dec.	11,860	315		Dec.	416	33.28	
Total	119,200	$3350	$3350	Total	6101	$502.88	502.88

Fixed charges		*Fixed Charges* Investment in plant, $11,000 Fixed charges @ 25 per cent	2,750.00
Manager's Time		*Manager's Time* One hour daily, 10-hour day @ $10,000 per year	$1000.00
Credit to Balance	3678.88		
Total	$7028.88	Total	$7028.88

A paper presented at the meeting of the Toronto Section, A. I. E. E., January 13, 1911, and also at the 259th meeting of the American Institute of Electrical Engineers, New York, March 10, 1911.

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THE COST OF INDUSTRIAL POWER

BY ALDIS E. HIBNER

It is hardly necessary to call attention to the rapidly increasing importance of industrial engineering subjects, a condition which has made possible the presentation of a paper on such a heretofore relatively unimportant subject as the cost of industrial power. To-day one can scarcely pick up a technical magazine without finding some article on an industrial engineering subject. The comparatively recent growth of this activity is evidenced to some extent by the fact that the Industrial Power Committee of the A.I.E.E. has been in existence only three years.

The editor of a technical magazine recently commented upon the slowness of the industrial world in recognizing that organized manufacturing was essentially an engineering proposition and that the industrial engineer was quite different from an electrical or mechanical engineer. The writer went on to point out that the distinguishing features were chiefly the economic and human elements of the problem.

I know of nothing which will illustrate more vividly these distinguishing characteristics than a five minute talk with a manufacturer on the subject of power. Nearly every manufactured article requires the use of power for the completion of at least one step in the process. Almost all articles require power for every step of the manufacturing process. This results in all manufacturers having some experience with the cost of power, and there are just as many opinions on the cost of producing power as there are manufacturers.

The economic features of the problem are quite clear. Every power user wishes to obtain his power at a minimum cost.

The introduction of the human element, however, quite often produces far different results. I have in mind one manufacturer who was so anxious to obtain his power (representing about 2 per cent of the cost of production) at a low cost that he neglected his legitimate business. The result was a loss of considerable magnitude in his business and a cost of power 38 per cent higher than the cost at which his power could have been purchased from a power company.

Another example of the importance of the human element, and what it involves in the popular misconception and ignorance regarding the cost of power, is given by the manufacturer who maintained that his gas producer plant was turning out power for $15 per horse power-year, and that water power at $20 was of no interest. A test on this plant showed a cost of $75 per horse power-year.

These examples are not exceptional or exaggerated aspects of the condition that exists among the average power users. The manufacturer, as a general rule, does not know within an accuracy of 100 per cent how much his power is costing per unit. He knows how many tons of coal he is purchasing each year, and the wages of his engineer and fireman, but he does not know how many horse power-hours have been produced.

A little consideration will demonstrate that this is not a surprising state of affairs. A concern is incorporated for the purpose of making shoes, or candy, or stoves. The manager is chosen for his knowledge and experience in the production of these articles. The superintendent of a shoe factory knows how to place a shoe on the market that will sell in competition with other makes of shoes, and, at the same time, pay dividends to the stockholders. If he is doing this he should have little time to devote to the manufacture of kilowatt-hours.

One would suppose that the manufacturer himself would be the first to recognize this fact and employ a consulting engineer to advise him in technical matters, but such is not the case. I know of one manufacturer who signed a contract for a power plant, costing $40,000, upon his own inexperienced judgment and the advice of the salesman who sold him the plant. Later investigation of this contract showed that, for cleverness in concealing the real facts, it would put to shame any shell game on record.

Sometimes manufacturers retain consulting engineers on the basis of a percentage of the cost of the plant if it is installed.

The dangers of such a practice are quite evident, as it is asking a good deal of human nature for a man to lose a neat commission on the sale of a plant by recommending the purchase of power. The manufacturers themselves are largely to blame for this practice, as they persistently refuse to pay an adequate fixed sum that will obtain for them the services of the best engineers.

Unfortunately the engineering profession, like that of the medical and the legal, has its quacks, and a manufacturer has to take the same care in selecting his engineer that he uses in selecting his physician. It is to be hoped that the present agitation of this subject will result in some method of eliminating this difficulty.

At present it is a too common practice for a man, who tells you that his own business has been developed by years of experience and study of conditions, to spend two weeks visiting this or that plant with a salesman, and, at the end of that time, thinks he has a thorough knowledge of the power problem. In fact he may go so far as one manufacturer and get you off in a corner and whisper in your ear that gas producers are going to shut down the water power plants.

A manufacturer can no more trust his business judgment in the purchase of a power plant than he can trust it to perform a surgical operation. The question in either case is one of technical knowledge as well as economics. The man who paid $40,000 for his power plant was an experienced business, man, but he honestly thought his power was guaranteed not to cost over one cent per kilowatt-hour, and did not notice that the sum set aside to cover interest, depreciation, insurance and taxes represented less than three per cent on the investment. Neither did he notice that the amount allowed for coal did not include charges for banking his boilers over night, and that in spite of this chicanery the contract, on the face of it, showed a cost of one and one-half cents per kilowatt-hour.

In view of this state of affairs, I believe considerable benefit may be derived by an outline of the different factors to be considered in the cost of producing power and a general discussion of the same.

The cost of producing power by large central station plants has been quite fully discussed by the Institute, but, while some of the principles involved are the same, there can be no direct application to the small industrial plants. In the one case we are dealing with stations of several thousand horse power capacity, in the latter with a plant of a few hundred. The central station is organized for the manufacture of electric power and the plant location is chosen with the object of producing power at the lowest possible cost. The industrial plant is organized for the manufacture of shoes, or what not, and other considerations are more important in its location. The former has every possible advantage in favor of cheap power, the latter very often everything against cheap power. There are other considerations which make the problem quite different, such as the use of steam for heating and industrial processes.

It is not at the present time, as formerly a question of electric drive versus mechanical drive, for nearly all the new private plants are electric. What the manufacturer wants to know is, "shall I purchase my power from a power company, or are my conditions such that I can produce it cheaper myself?" It is some of the factors entering into a solution of this question that I wish to discuss in this paper. Every factory has conditions peculiar to itself which require special attention and prevent any general deductions. This does not mean, however, that the solution of a typical case will not be of value in showing the relative importance of the different factors.

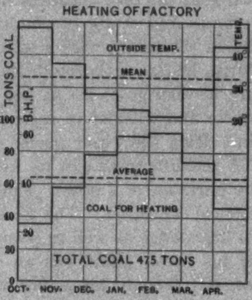


FIG. 1

There are in general three factors involved in every industrial power problem; the investment charges, operating charges, and the cost of heating or use of low pressure steam. The investment charges are understood to cover the interest, amortization, insurance, taxes, and profit on the capital invested in the plant. The operating charges include coal, labor, repairs, and supplies. The cost of heating is the investment and operating charges of the boiler plant necessary for heating the building and supplying steam for manufacturing processes.

A typical example of the conditions ordinarily found, we will say, is the Blank Shoe Co. which has outgrown its present quarters and has decided to build a new factory and eventually double its output. The new building is to be of brick, four stories high, 250 ft. (76.2 m.) long and 60 ft. (18.2 m.) in width. This gives a total of 60,000 sq. ft. (5574 sq. m.) of floor area and a content of 750,000 cu. ft. (2023 cu. m.).

One of the first things which must be determined before starting construction is whether power will be purchased or supplied from a private plant. The first step in the solution of this problem is to determine the cost of heating the building. A heating plant is necessary in any case, as the conditions of manufacture are such that the temperature of the building must be kept above fifty degrees during the winter months.

Fig. 1 shows the mean monthly temperatures for the seven winter months at Toronto. The lower curve gives the coal per month necessary to heat the building to a temperature of 65 deg. fahr., the same curve to a different scale giving the average boiler horse power required. The coal consumption is based on an evaporation of seven lb. of water per pound of coal (7 kg. of water per kg. of coal) one change of air per hour in the factory and the supplying of radiation losses. During zero weather 90 boiler h.p. will be required. Having determined the size of boiler plant necessary we are ready to take up the cost of heating.

TABLE I

HEATING PLANT INVESTMENT.

Boiler, piping and auxiliaries, (A)	$1,500.00	
Building and stack, (B)	2,500.00	
Total investment	$4,000.00	
FIXED COST		
Interest 6 per cent on $4,000	$240.00	
Insurance and taxes, 2 per cent on $4,000	80.00	
Amortization on A, 4½ per cent, 15 year life	67.50	
" " B, ½ " 50 " "	12.50	
		$400.00
OPERATING COST		
Coal, 475 tons @ $3.00	$1,425.00	
Fireman @ $15.00 per week	780.00	
Supplies and repairs	100.00	
		2,305.00
Total cost		$2,705.00

Table I gives the investment necessary, together with the fixed and operating costs of the plant.

Replacement of the plant has been provided for by a sinking fund drawing 5 per cent interest compounded semi-annually, based on a life of the various parts of the plant as given in the table. The time of the fireman has been figured for the entire year, as steam at high pressure is required the entire year for industrial purposes. It is of interest to note that the cost of coal represents only a little over 50 per cent of the total cost of heating, and that a variation of 25 per cent in the amount of coal burned causes only 13 per cent variation in the total cost.

Having determined the expense which is absolutely necessary in connection with the power requirements, the question asked is whether it is advisable to go a step further and make the additional investment necessary for generating power, or whether it shall be purchased from a power company. The answer, obviously, depends upon the additional cost of producing this power and the rate at which power can be purchased. Having determined the former, the rate at which power can be purchased to advantage is fixed.

TABLE II

COMPLETE POWER PLANT INVESTMENT

Capacity, 100 kw.

Engine, generator, switchboard, wiring (A)	$5,500.00	
Boilers, steam piping, auxiliaries, (B)	5,000.00	
Building, foundations, stack, (C)	5,000.00	
		$15,500.00
Steam heating plant		4,000.00
Additional for power		$11,500.00
FIXED COST OF POWER PLANT		
Interest, 6 per cent on $15,500	$930.00	
Profit, 5 per cent on $11,500	575.00	
Insurance and taxes, 2 per cent on $15,500	310.00	
Amortization on (A), 3 per cent (20 year life)	165.00	
" " (B), 4½ " (15 " ")	225.00	
" " (C), ½ " (50 " ")	25.00	
		$2,230.00
Fixed cost on heating plant		400.00
Additional for power		$1,830.00
OPERATING COST OF POWER PLANT 240,000 kw-hr.		
Coal @ 7.39 lb., 887 tons @ $3.00	$2,661.00	
Banking, 181 tons @ $3.00	543.00	
Night heating, 202 tons @ $3.00	606.00	
Engineer @ $18.00	936.00	
Fireman @ $15,00	780.00	
Water	100.00	
Oil, waste, supplies	150.00	
Repairs	200.00	
		$5,976.00
Operating cost of heating plant		2,305.00
Additional for power		$3,671.00
Total additional for power		$5,501.00
Cost per kw-hr.		$0.0229
Cost per h.p-year		$51.40

The concern under consideration has a maximum demand for power of 100 kw. (134 h.p.). The average load is 80 kw. (107 h.p.) giving an 80 per cent ten-hour load factor. The engine is a Corliss non-condensing, requiring 30 lb. (13.6 kg.) of steam per indicated horse power-hour. The boiler evaporation is taken at seven lb. of water per pound of coal, (7 kg. of water per kg. of coal) giving a coal consumption of 4.3 lb. (1.95 kg.) per indicated horse power-hour. The efficiency from steam cylinder to switchboard is 78 per cent, giving a coal consumption of 7.39 lb. (325 kg.) per kw-hr. or 5.51 lb. (2.5 kg.) per h.p-hr. at the switchboard. The factory runs 300 days per year.

In Table II is given the investment cost, fixed cost, and operating cost of the plant. Allowance is made for the cost of heating, as calculated above.

Among the items of fixed cost will be found one covering a profit on the additional investment required for a power plant. It is quite clear, I believe, that a concern is not justified in investing in a power plant, unless the capital so invested returns the same profit as if invested in the most profitable part of the business still capable of extension. When the added risk is taken into consideration, I think this could safely be raised to 10 or 15 per cent.

There is nothing, I believe, among the items of operating cost that requires explanation, with the possible exception of the night heating. The engine is only running ten hours per day. It is evident then that, unless live steam is supplied to the heating system during part of the remaining 14 hours, the temperature will fall below that safely allowable. This feature is too often overlooked by the average power user. He thinks that if he installs an engine his heat will cost him nothing, forgetting that every night his watchman is turning live steam into the heating system for a length of time depending upon the temperature outside.

In Fig. 2 an attempt is made to show graphically the relative quantities of coal necessary for power and heat. The area double cross latched represents the saving in coal effected by using the engine exhaust for heating the factory.

It is evident from these results that if power can be purchased for 2.3 cents per kw-hr. there is no advantage in installing a steam power plant. At the present time, however, an engineer would scarcely make any decision without investigating the cost of producing power by means of a gas producer plant. Before taking up this question, I wish to call your attention to the fact that a 50 per cent increase in the amount of coal required for heating causes only a 9 per cent reduction in the cost of power. I should like, in contrast to this, to show the effect of a variation in the ten-hour load factor.

By load factor I mean the ratio of the average load to the maximum load for a given period of time; in this case ten hours. I wish to mention here that 90 per cent of power users do not know the load factor of their factory. Nearly all of them will tell you that their load is absolutely constant. The point was brought home very forcibly to one manager when a graphic wattmeter was installed and he could see with his own eyes that it took half an hour for the men to get their work started in the morning, that they began to stop working half an hour before noon, and that the same performance was repeated in the afternoon in starting and stopping. Under the best conditions it is difficult to get a load factor of 80 per cent, while printing and machine shops only have 40 or 50 per cent.

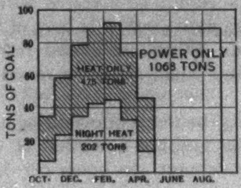


FIG. 2

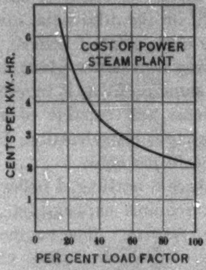


FIG. 3

In the assumed conditions the load factor was taken at 80 per cent. It is seen from Table II that the only items which will be affected by a reduction of the plant output are the first item of coal, and the water. The amount for water is so small as to be negligible. The first item of coal represents roughly 48 per cent of the net cost of power. A decrease in the load factor from 80 per cent to 40 per cent will, therefore, decrease the output 50 per cent and the cost of production 24 per cent, increasing the cost per kilowatt-hour 52 per cent or to 3½ cents per kw-hr. Plotting a curve for different load factors and the corresponding cost, we get the result shown in Fig. 3.

The heating is assumed constant, and this introduces a slight error for load factors under 30 per cent, as the average load on the engine then becomes less than the average heating requirements and necessitates supplying live steam to the heating system during the daytime. The main idea is to show that, while the average manufacturer does not know the load factor on his factory, it is the most important element in his power cost.

The curve will further serve to show the mistake which nearly every manufacturer makes of figuring his power on a horse power-year basis. In the case of the above plant the manufacturer would consider that he had a load of 134 h.p., the maximum demand. As the maximum demand remains constant for all load factors, the cost per horse power-year figured on that basis would be about $41 at 80 per cent load factor and $31 at 40 per cent load factor, a decrease of 25 per cent instead of an increase of 50 per cent. The cost per horse power-year based on the average load is $51, as given in Table II, for 80 per cent load factor and $78 at 40 per cent load factor. In this latter case the actual cost per unit is over 2.5 times that figured by the manufacturer.

It is interesting to note the effect of the use of exhaust steam on the cost of power.

If all the exhaust steam from this plant were necessary for industrial purposes, the only additional investment necessary to produce power is the $5,500 for an engine and generator. The fixed cost on this amounts to 16 per cent or $880 per year. The extra operating cost is an engineer at $936 and $250 to cover oil, waste and repairs, giving a total of $2,066 for generating 240,000 kw-hr., giving a net cost of 0.86 cents per kw-hr. It is quite evident from this that the amount of low-pressure steam that can be utilized plays a very important part in the cost of power.

GAS PRODUCERS

The most active competitor of the steam engine for power production is the gas producer plant. This type of plant, which has developed since 1900, has shown remarkable economy of coal consumption when handled by experienced operators. The United States Geological Survey Report on Gas Producer Plants shows that for an average of a great many tests the non-condensing steam plant requires 2.7 times as much coal per unit as the producer plant. Their results give a thermal efficiency at the switchboard of 4.86 per cent for the steam plant and 13.5

per cent for the producer plant. The maximum attainable efficiency is probably 10.3 per cent for the steam plant and 21.5 per cent for the gas producer under present conditions. In view of this known economy a great many producer plants have been installed in the last few years.

For the factory under consideration the conditions will require the installation of a 175-h.p. engine and producer, and in addition a heating plant for heating the building. As this heating plant is required in any event, the cost of heating is eliminated as a comparative factor in the problem. The investment, fixed costs, and operating costs of this plant are given in Table III. The cost of the plant is somewhat higher than the corresponding steam plant. The life of the plant is also shorter. This gives a higher fixed cost than for the steam plant.

TABLE III

GAS PRODUCER PLANT

INVESTMENT		
Engine and producer (A)	$11,900.00	
Generator, switchboard, wiring, (B)	2,500.00	
Building, (C)	2,500.00	
	$16,900.00	
FIXED COST		
Interest, 6 per cent on $16,900	$1,014.00	
Profit, 5 per cent on $16,900	845.00	
Insurance and taxes, 2 per cent on $16,900	338.00	
Amortization on A, 15 year life, 4½ per cent	535.00	
" " B, 20 " " 3 "	75.00	
" " C, 50 " " ½ "	12.50	
		$2,819.50
OPERATING COST 240,000 kw-hr.		
Coal, 3 lb. per kw-hr. @ $4.00, 360 tons	$1,440.00	
Engineer @ $18.00	936.00	
Oil and waste	125.00	
Repairs	300.00	
Water	133.00	
Emergency service	300.00	
		$3,234.00
Total		$6,053.50
Cost per kw hr	$0.025	
Cost per h.p-yr	$56.20	

The operating costs of the producer plant are only about one-half that of the steam plant. This, however, is counterbalanced by the cost of heating. The final result gives a slightly higher cost for the gas producer plant. The ratio of the fixed cost to operating cost in the two cases, however, produces a very marked effect where the load factor is poor. The only items effected by the output of the plant are coal and water. These represent only about 27 per cent of the total cost, as against 50 per cent with the steam plant, the result being a very much higher cost for the gas producer at low load factors. The poor fuel economy on light loads would further exaggerate this effect. Fig. gives the cost at different load factors.

The dotted lines are a reproduction of the steam plant costs given in Fig. 3.

It is quite evident that where the use of exhaust steam amounts to anything, a steam plant can show greater economy than a gas producer plant. For a 24-hour load with only a small demand for steam to heat the building, the gas producer is the most economical.

I believe that the cost of power, as worked out in the two cases just given, represents a condition which will be found most often. Twenty-four hour services and condensing plants are the exception and not the rule among the factories under discussion, and it would not be worth while to lengthen this paper by including them.

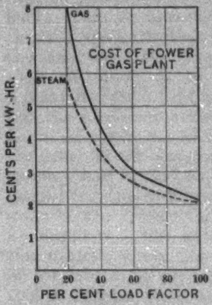


FIG. 4

I am very strongly of the opinion that manufacturers lose perspective in judging of the importance of the cost of power in comparison with other factors in their cost of production. It is rarely that the power cost represents more than 2 per cent of the cost of the manufactured article. A saving as large as 25 per cent in the cost of power then only reduces the total cost ½ per cent. Balance this against the item of labor which often represents 50 per cent of the cost of production. A saving of one per cent in this factor accomplishes the same result as a 25 per cent reduction in the cost of power. It seems to me that the chances of a one per cent reduction in labor cost is greater than a 25 per cent saving in power cost, when it is considered that a manufacturer is quite expert in labor matters and inexpert in power conditions.

Recently I read an article on the effect of factory ventilation on improving the efficiency of workmen, and it appeared that an increase of 25 per cent in the factory output was possible under certain conditions, if a proper ventilating system was installed.

Compare the relative importance of this saving with a few hundred dollars possible in the case of the same money invested in a power plant.

The time is rapidly coming when the small power user will take all these economic and technical questions to a consulting industrial engineer for solution, just as he takes his legal questions to a lawyer. The large manufacturing companies are already doing so; and in a few years the purchasing of power plants by factory owners, without any consulting engineering advice, will be a thing of the past.

DISCUSSION ON "THE COST OF INDUSTRIAL POWER", TORONTO, JANUARY 13, 1911.

A. M. Dudley: It is common information among the men who are doing industrial engineering, that factory power users have the most diverse methods of figuring the cost of their power, and that very often their ultimate conclusions are as erroneous as in the case of the user mentioned, who honestly believed that his power was costing him $15 per h.p.-yr., where, as a matter of fact, it was really costing five times as much. This error, as pointed out, arises not so much from error in figuring the cost of all the power used in the aggregate, as in an error as to what is the actual amount of power required and used. One great element in causing this error is that of load factor, and as Mr. Hibner points out, it is also one of the largest factors in determining the actual cost of the power. Load factor is defined in this paper as the relation of the average to the maximum load. This at once suggests two things; first, that a plant load factor is made up to a considerable extent of the load factor on the individual machines. As it is a fact that all machines run most efficiently at or somewhere near their full load rating, a plant having a load factor of 50 per cent, which is made up of half the machines running under full load all the time, may have a cost of power per kilowatt-hour less than another plant having the same 50 per cent load factor but made up of all the machines running half loaded all the time. This is one urgent reason why careful tests on individual machines should be run to see whether units of the proper capacity have been selected for the various applications. The writer has in mind a plant driven by induction motors where the plant power factor was brought up from 35 per cent to 65 per cent simply by shifting the motors from one tool to another more nearly fitting its capacity, and the purchase of one or two new units of the smallest size at the bottom of the line. This not only directly reduced the operating cost by running the motors at their most economical load but had it been properly anticipated on the original installation, would have permitted the use of a smaller generator with consequently reduced investment charges.

The second suggestion in regard to the question of load factors is that users are apt, in figuring their power consumption, to take the capacity from the name plate of the driving motor or motors and consider that as the average consumption. If, as is more often the case than not, this unit has been liberally allowed for, the ultimate calculated consumption of power is in error by even more than the ratio of the maximum to the average consumed. When these facts are considered, it is not so hard to understand why the cost of power is sometimes figured in error by 400 per cent. As an illustration of how serious this error may be, figures are submitted showing the ratio of the *average load* to the *connected load*, which are the result of a number of observations and fairly represent the average condition. These figures are as follows:

Cement mills, 85 per cent.
Textile mills—cotton and woolen, 75 per cent to 90 per cent.
Tanneries, 55 per cent.
Ice machines and refrigerating plants, 53 per cent.
Marble works, 51 per cent.
Flour mills, 50 per cent.
Carriage and wagon works, 35 per cent.
Machine shops, 35 per cent.
Breweries, 33 per cent.
Boiler shops, 28 per cent.
Sheet metal manufacturing, 27 per cent.
Soap manufacturing, 28 per cent.
Rubber manufacturing, 25 per cent.
Wood working, 10 per cent to 35 per cent.
General average of all industries, about 33⅓ per cent.

Another point which the paper brings out and which merits recognition is the utility of the graphic meter in recording not only the actual power consumption in laying bare errors of this nature, but its secondary use of indicating interesting and pertinent facts regarding the management of individual machines and the conduct of the entire factory. For all these reasons, tests based upon graphic meter charts are most valuable in settling the much mooted question of power costs.

One of the most valuable deductions is that the cost of power must be kept in its proper perspective with regard to the total cost of production in an industrial plant and that after all, it amounts in general to perhaps the astonishingly low figure of 2 per cent. This is probably the real reason why we have not in the past had more investigation of this subject, but it must be accepted with modifications, and one of the chief of these is that while the cost of power in industrial plants is a small proportion of total cost, the cost of interruptions to the power may cause serious disaster. From this, we may draw two conclusions; first, that continuity and reliability of service must have their due consideration in balancing the central station supply against the private plant and, second, whatever makes for reliability and continuity of service, even at some sacrifice of economy in detail, may be installed and will ultimately prove the greater economy through insurance of uninterrupted output. This brings the conclusion that Mr. Hibner had perhaps better split up his generating units and put in some reserve capacity. When the necessary investment charge is added to take care of this I believe, the paper will cover all the elements that go into the problem and furnish in addition, valuable data on the solution of a specific case.

E. Richards: There is one matter that I wish to briefly comment upon before calling on some of the other members to take part in the discussion. I have no thought of criticising Mr. Hibner's paper. I think that his values have been carefully chosen. I had occasion to check up some of them and I think that the average represents very good, typical, modern practice. I am, however, interested, and somewhat amused, from one standpoint, in the view that is taken of the typical basis of power cost. The central station man makes the cost of the unit of power the basis for comparison, and he gets into the way of thinking only in kilowatt-hours. Now it is not at all apparent to one who has studied the power question from a general standpoint why this should be so prominent. Such is not the basis of cost of power in any case. The cost of power is not based on the kilowatt-hour; it is not the central station man's basis of cost but it is his method of selling, and the time may come and I believe is coming when we will break away more or less from this basis of comparison of power cost. As transmitted power becomes more prominent in power problems with its accompanying high fixed charges, the kilowatt-hour will become somewhat relatively less important. The kilowatt-hour may figure for convenience in cases where the actual power consumed by any user does not figure in the maximum demand coming upon the generating apparatus of the plant or station, but apart from that it is only a convenience in the selling and measuring of power. But in cases of transmission the much higher factor in the power cost is the demand that it brings upon the plant because of the relatively large fixed charges.

Ivar Lundgaard: There are a great many factors in power generation of which we do not possess sufficient statistics to judge rightly, and it is only by the action of such bodies as the Institute that we can obtain such data. Mr. Hibner's paper has been very clear in defining the various factors and really does not leave much to be said when it is limited only to the cost. What I am going to say in the following has a bearing on the so-called fixed costs.

One of the most notable facts about power generation is that improvements have been made at a steadily increasing rate. The last ten years have seen more real improvements in power generation than any previous period of the same length, and some that have been made in the last couple of years assure me that the progress is not going to be retarded. I think we will see still greater developments in the future than we have seen in the past. I cannot go into the subject of improvements very largely but I can mention a few.

There have been enormous advances made in the art of long distance transmission, the size and efficiency of steam turbines have grown, the oil engine and also the gas engine have been developed in the last ten years. Power plants have been improved in arrangement with resulting economy of space and labor, and, on the whole, it has resulted in materially reducing the cost of power. It is also worth noticing that the central station has always been the first to take advantage of any real advance that has been made in power generation. The manufacturer cannot readily follow the times because he has 98 per cent of other things to do, and when he has his money tied up in a plant, that plant will go on producing power at the given cost until its natural departure to the scrap-heap, unless it has an earlier death as has been so often the case recently. In such a case, of course, the value of the plant is lost. There have been a great number of such early deaths of private plants in recent years, and that should cause serious consideration. Another thing that adds to the importance of this, is the fact that the private plant dies hard. There are many reasons for this. No factory can tell to-day what its business is going to amount to in five years from now. Its business may increase or it may decrease, and one thing is sure, that a factory cannot stop growing because its power plant is too small. It has to keep on adding units to the power plant. While that may be all right, it usually results in a very undesirable type of plant. The multiplication of units means more attention, more repairs, more labor, lower efficiency and so on. Now, suppose that a factory with a plant of its own is placed in a position where it might possibly buy power from outside sources at a cheaper rate than it manufactures power itself. You see where the fixed costs hold them. They cannot take advantage of cheaper power unless their plants happen to be in extremely bad shape. Suppose a manufacturer starts in business at a time when a great development has been made in power, and installs a plant very much superior to that of his older competitor. The first plant will find itself at a disadvantage in the competition because it has a plant that costs so much more to run. Suppose a factory goes out of business or wishes to move the power plant. In both cases it represents only so much expense or loss in moving or in having to be sold. Suppose a conflagration destroys part of the factory. It does not matter whether this part is the power plant or the factory itself. The business is going to suffer a loss, because the business loss cannot be compensated for by insurance. No insurance company will compensate for stoppage of business on account of a boiler explosion. It only reimburses you for the cost of the buildings or a few large losses, perhaps, but not for stoppage of business. I am well aware that there are risks in all businesses, but it is worth while considering if it is not better from an investor's point of view, to avoid investments in a power plant that will not yield a substantial profit when compared with the cost at which power can be purchased. Any conservative business man will hesitate before spending a large sum of money on a proposition that is so uncertain from a profit-seeker's point of view. There is one argument frequently brought into the discussion, and that is, the manufacturer wishes to be independent. It is safe to say that the same manufacturer is tied hand and foot when he has his money invested in a private plant. As long as he uses the central station power he is free to decrease or increase his business without suffering from the consequences of excessively heavy investment charges, or he can discontinue his business or do anything he likes, and he will be much less likely to have interruptions on account of strikes and labor difficulties.

Mr. Hibner brought out the fact that it is important for a man in the manufacturing line to devote his time to his business. I believe there is an old adage about that. You may ask what all this has got to do with the cost of power. Mr. Hibner has shown that the fixed costs amount to about 50 per cent and that the fixed cost largely depends upon the amortization, which again depends upon the life of the plant. Now the life of the plant is usually considered to be the length of time that the engine can possibly keep on turning the flywheel, but I believe I am justified in objecting at this point, because we should not consider the possible life of a plant but the useful life of a plant. I have been trying to obtain statistics as to the useful life of a plant, and I have been looking for them far and wide. I know that some plants go on living after they should have been retired and put on the pension list; I know that some plants have been giving useful service all their lives, and I know that some plants should never have been built.

Now the question of useful life is of such importance I wish to call attention to it and emphasize the necessity of collecting such information that will put us on a firm basis as to where we stand on this item.

I see one objection to one of the figures in the tables. The building is put down at $2500; the fixed cost is 1½ per cent. The plant is given a twenty year life. Now when that plant is out of business the probability is that the building itself will be useless. Therefore I think it is a good practice to figure the depreciation on the building, the same as that of the plant. I think that our common sense and observation tell us that when the plant has ended its useful life the building does not fit the new condition that will surround the new plant.

A. S. L. Barnes: There is one point I wish to speak of and that is the cost of obtaining power from a generating station against that of generating it on the premises, and transmitting it either electrically or mechanically. In the former case the manufacturer does not have to pay for any power he does not use nor for the standby losses at noon and other periods of stoppage which in the case of some plants is pretty heavy. In the case of obtaining power from an outside source the manufacturer saves all that and the cost of keeping the boiler and the steam pipe hot. If the steam pipe mains are of any considerable length, it is usually a considerable item of the total cost of the coal, and personally I think a certain amount for coal ought to be put down for fixed costs for whether you are using any power out of the coal or not you have to pay for it. In the case of a generating station if you imagine the necessary engines running but not supplying any power, in most cases I think it would be found that the coal used under these conditions, without turning out a single unit, would be a very fair percentage of the total cost used under ordinary conditions. I had an opportunity of testing that to some extent some years ago, and it worked out to be about 6 per cent, and as coal in that instance was 50 per cent of the total expenses of running the station the fixed charge for coal was pretty considerable for the twelve months.

A. E. Hibner: There are one or two points brought up in Mr. Dudley's discussion I would like to speak of. He emphasized the importance of having the motors which are of the right size for the work to be done and showed how the power factor can be increased, and had been increased in several cases by doing this. Increasing the power factor, of course, increases directly the capacity of the generator. Thus, obtaining a higher power factor would mean a smaller generator than would otherwise be necessary. The motor cost itself of course would be decreased, the smaller motors costing less. The efficiency of motors as Mr. Dudley points out are best when running at their full load. This does not mean, however, that a 15-h.p. motor running on a 7-h.p. load would not be running as economically as a 7-h.p. motor at full load. In fact the efficiency that is obtained by a 15-h.p. motor running at half load is as good as a 7-h.p. motor at full load. The main thing is to have the motor small enough so as not to have a lot of money tied up unnecessarily.

Mr. Richards brought up the point of charging on the basis of the kilowatt-hour. Most all power companies are now getting round to a system whereby they charge a fixed amount plus kilowatt-hour rate; that is, a fixed amount which would be compared with the fixed cost on the steam plant, plus a kilowatt-hour operating charge. In fact, some companies are coming to a three rate system. A fixed sum, say, of $30 a year which covers the cost of reading the meter and so forth, in other words a sum which is in proportion to the number of consumers on the line whether they use the power or not; then a charge of so much per horse power of maximum demand, then a kilowatt-hour charge.

Mr. Lundgaard has brought out the point that considering the risk involved the item of profit of 5 per cent can very well be increased to possibly 10 or 15 per cent.

A. L. Mudge: In any discussion on the cost of industrial power we should strongly emphasize the distinct advantages obtained by distributing and applying power electrically as against transmitting it by shafting, belts and other mechanical means. Mr. Hibner states that the cost of power in many cases is not more than 2 per cent of the cost of the final product. Even if we forget all about the relative cost of producing power by different means, the arguments in favor of electric drive in factories would be just about as strong. The following are some of the advantages which result:

First, the machines can be located in such a way as to best facilitate production, for it is not necessary to locate a machine so as to line up with a certain countershaft.

Second, where heavy work is done, every machine can be served by an overhead travelling crane, as there are no countershafts, belts etc., to interfere.

Third, where a change of speed in machines is of value, for example, on lathes, boring mills, etc., such speed variation is readily obtainable to a very fine degree and inside of wide limits, and this without stopping the work for an instant.

Fourth, on account of doing away with belts, shafting and hangers the lighting is greatly improved, greater cleanliness and safety are obtained.

Fifth, on large work portable tools can be freely used, thus the tools can be taken to the work instead of the work to the tools.

Sixth, certain departments or single tools in the factory can be run at night without having to run the main engine and most of the shafting. This applies more particularly to the case of power obtained from a central station when it is only necessary to close a switch to start the motor instead of bringing in the fireman and engineer in order to furnish power for the work of perhaps two or three men.

Advantages such as the above may give economies which will decrease labor cost or increase rate of production in such a way as to save the total cost of power several times over, and the way we should look at this question is that the immense advantage in electrical drive in factories is not merely in decreasing the power cost, but in the increased efficiency both of men and machines, due to the great flexibility of the electric drive and the improved conditions generally which it creates.

DISCUSSION ON "COMMENTS ON FIXED COSTS IN INDUSTRIAL POWER PLANTS", AND "THE COST OF INDUSTRIAL POWER", NEW YORK, MARCH 10, 1911.

Percival Robert Moses: The paper presented by Mr. Parker purports to be a discussion of the cost of power generation and certain features in connection therewith in small plants of the industrial type. Such plants are usually understood to mean manufacturing establishments, but the tabular data presented apply to department stores and have nothing whatever to do with industrial plants as usually understood. I shall discuss this tabular data later.

Taking up the paper in detail, reference is first made to the marginal principle. This principle, as I understand it, is the principle enunciated by Wellington in his theory of street railway location, *i.e.*, that no expenditure is justifiable unless in itself it will earn a fair return. The author states in the following paragraph that since the installation of a plant, costing $10,000 to $20,000, would constitute a physical improvement to the property, it is obvious that the tax assessment will be increased thereby. Practical experience points the other way. I have never had the taxes increased on any building or manufacturing establishment because of the installation of a small private plant; nor, on the other hand, do I know of any decrease in taxation resulting from the shutting down of such a plant.

Regarding insurance, he also discusses the question of insurance and, later on, allows 3 per cent for taxes and insurance. I have already discussed the question of taxation, and the question of insurance is usually one of small moment. The rate in modern fire-proof buildings rarely exceeds one-quarter of one per cent on 80 per cent of the actual value. This is for fire insurance. If to this be added the liability insurance, the total additional insurance due to the operation of a private plant will, even theoretically, not exceed one per cent of the cost of the plant. I say "even theoretically", because unless a plant is quite large, *i.e.*, around $30,000 or $40,000 in value—the amount of insurance on the building is rarely changed. As for the liability insurance, it will usually be found that the labor increase in an industrial plant, due to the installation of a small private generating plant, is inconsiderable and, as the liability premium is figured as a percentage of the pay roll, the *addition* to the liability insurance premium which is the only part that should be charged to power generation is usually nominal. Of course, the matter should be considered, but it should be considered practically and the actual cost allowed not an imaginary cost.

This expense for liability and fire insurance, the author states, is existing whether such insurance is actually carried or not. The fact is lost sight of that the presence of an electric plant, with its additional employees, is an additional safeguard against fire, and if we begin to allow for theoretical additions to insurance we should also allow for theoretical increase in efficiency of fire protection.

The author's discussion of the depreciation of a plant seems entirely fair, except that I believe that in an industrial plant, where the plant is liable to increase in size or to change its character, the depreciation rate should cover the possible obsolescence of the machinery. This is a matter which must be determined in each case by the possibilities of the case.

The author's discussion of the supervision of a plant does not seem to me to be well based. He discusses the possible proportion of the time of a manager which may be taken up in connection with the power plant, then allows for the possible value of this man to the concern and the possible profit that might be obtained from the use of this man's whole time if he were not distracted by the power plant. He forgets to allow for the increased efficiency of the manager due to his increased knowledge of power generation, and that the manager through his connection with the operation of a power plant may learn something that may enable him to double the output of his business. I am treating the matter sarcastically because if we go into possibilities, or, as they were called in the Alabama Arbitration, indirect claims, we will never get at the facts. I believe that it is proper to charge against the plant operation the actual cost of such time as is required for supervision *of the power plant required for the generation of electricity*; *i.e.*, the additional time of the manager that is required to supervise the operation of the electric generating plant—not the time required for supervising the operation of the boilers or deciding questions in connection with the power transmission or with the motors or with the air compressors, but solely the time required in connection with the electric generating plant. If this time is analyzed, it will be found to amount to a few hours during a year—not a few hours a week. And even this amount of time is partly balanced by the services rendered by the operators of the electric generating plant in other parts of the works.

After allowing for interest on the investment and depreciation and possible obsolescence, and taxes and insurance which do not exist in most cases, and for a very large proportion of the time of the superintendent at $10,000 a year the author of the paper proceeds to add a fair profit based on the average profit in the store.

If this paper were an argument in favor of central station service and not an unbiassed investigation of the cost of industrial power, such a proposal might be understood. On the same theory, the rent of the building should be charged at the average profit obtained by selling merchandise—not at what the money could be borrowed for. And, in fact, the merchant could figure that he had no profit at all, because if he had to pay the averaged profit ratio as interest on all the money he borrowed from the bank, there would be no profit. On the author's theory, therefore, we would have clearly proved that the manufacturer or business man had no business to be in business at all.

The recognized and standard method is to charge interest on the investment at the rate at which money could be borrowed, and this interest on the cost of the electric plant is just the same as the interest on the cost of a building or the interest on the cost of an elevator machine; it is part of the rental paid and has nothing whatever to do with the ratio of profit on the sale of merchandise.

The next item in the discussion is the building space and real estate. This is a matter that must be considered in each case. In some cases it is true that the space taken up by the electric plant is valuable and a fair rental value must be assessed against this space. In fact, it may be stated that in all large plants this is the case. But in small plants, of which the paper treats, the reverse is true; and it is the exception rather than the rule that the space taken up by the private plant is space which may be used for other purposes. It is usually space required because of allowance for other machinery, and because of the objection on the part of the builder to place himself entirely in the hands of an outside company.

Appendix A is an interesting discussion of the marginal principle, but like most general discussions its application to special cases requires careful consideration, and Appendix B is a mathematical discussion of amortization or depreciation, as it is usually called. It is interesting to note that the author uses six per cent in this mathematical discussion, whereas on the fair profit theory it would seem more correct to allow the average ratio of profit.

Appendix B, which is the part of the paper that would most appeal to the ordinary business man, contains tabulated statements of figures "presented to and endorsed by the owner and manager of a large mercantile establishment." The figures may have been endorsed by a business man, but they are certainly not correct insofar as standard practice is concerned. The plant consists of a 100- and a 50-kw. unit. The cost of the engines, dynamos and switchboard is placed as approximately $9,000. The engines are high-speed engines. The actual cost of a 100- and a 50-kw. unit, delivered and erected on foundations ready for steam and electric connections, could not exceed $6,000 and I have recently purchased similar equipments for $5,500, as compared with approximately $9,000 given by the author. Similarly, boilers for 150-kw. units should not cost $6,200. Of course, if boilers were to be installed to take care of every thing else in the building besides the electric equipment they might, but the cost assignable to the power plant is certainly not correctly stated at $6,200.

The total given by the author is $20,265 for a 100 and a 50-kw. machine erected and connected, with the necessary boilers and stack. I presume that this is all in addition to the heating equipment cost and boilers required for other purposes. This is at least 50 per cent too high a cost. Not over two weeks ago, orders were placed for two 100-kw. direct connected, high-speed engines, with the necessary additional boiler capacity required for their operation, smoke breeching, steam fitting, wiring, switchboard, at a total cost of $13,000 including engineering charge.

Table 2 shows marginal interest 6 per cent, amortization 2.63 per cent, taxes and insurance 3 per cent, and fair profit ratio (this is in addition to interest) 11.5 per cent, or a total of 23.13 per cent. In my opinion if we allow 6 per cent interest, depreciation 2.63 per cent or even 5 per cent would be more safe, and taxes and insurance 1 per cent we have a total of 12 per cent on a correct installation cost of not over $12,000, or $1,440 per year for fixed charges, as compared with over $4,441 allowed by the author.

I have gone into details in this matter, as this shows how a little added to this item and a little added to that item, and a percentage charged here and a percentage charged there, each so small in itself, may entirely change the facts.

The same thing is true of the gas engine plant next cited, a small plant of 120 h.p., using producer gas produced from 4.5 lb. of coal per kw. hr. Our records from several such plants, operating under poor conditions, show less than 2.5 lb. of coal per kw. hr. A plant recently installed at Stanley G. Flagg & Company's works, Pottstown, Pennsylvania, a 175-kw. plant, ran for a month under regular working conditions with no allowance extra for banking; *i.e.*, the actual coal used for all purposes, was 2.05 lb. per kw. hr., less than one-half that allowed by the author, and this was No. 1 buckwheat coal.

The amount of coal and the cost of labor allowed seem about correct in Table 3, except I do not see why it is necessary to have a night engineer all the year around, whereas when the plant is only used for heating the fireman is only kept at night for 20 weeks. It is evidently not for generating electricity, because an allowance is made for emergency service.

The main discrepancies come under the head of Fixed Charge, which is estimated at $4,441, whereas correctly, as has been stated, this should not exceed $1,440, a difference of $3,000. $1,000 a year is allowed for the manager's time at $12,000 a year rate, it being assumed that the manager will lose this amount of time in connection with the power plant, which he would otherwise use, and that this time will be solely devoted to the electric generating end of the plant as distinct from the rest of the heating plant and power plant.

The space value is stated at $1.00 per sq. ft. This is space—not boiler space—in addition to that required for boilers and other machinery in the basement. The usual rate for basement space is from 10 cts. to 25 cts. per sq. ft. and, in some rare cases, 40c. per sq. ft., particularly for space in the middle of a store basement.

Altogether, there seems to be about $4,200 charged against the plant operation which should not be so charged, making the actual cost of the power plant operation $8,763 as compared to over $10,000 with the central station service. It should be noted that the table only allows $25.00 a year for the manager's time, including clerical expense, with the central station service, whereas $1,150 is allowed with the private plant, and the only addition in the machinery line has been the self-oiling engines and dynamos and their connections.

In the gas engine plant, Table 4, 25 per cent is charged for fixed charges, as compared to 12 per cent. The coal per kw. hr. is stated at 4.6 lb., whereas the usual ratio for producer gas engines is a little over 2.25 lb., and this includes coal used for banking. No provision is evidently made for re-circulation of the water, and the allowance 27.2 gal. per kw. hr., is greatly excessive.

One thousand dollars a year is allowed for this little bit of a plant for manager's services. An engineer is charged for extra, presumably in addition to the man operating the heating plant. For a plant of this size, one man should be able to do both, and usually does.

Altogether, the figures presented do not seem to represent even fair average practice, and the allowances for fixed charges and manager's time cannot, in my opinion be defended upon any reasonable ground.

In general the paper is an argument for central station service, and is not an investigation of the cost of industrial power.

David B. Rushmore: Industrial plants are rather sharply divided into separate classes. In the large cities one finds many small industrial plants of a few hundred horse power each, some directly connected to a central station. There also exist other plants of this nature which demand many thousands of horse power, where the desirability of connection to a central station is not so apparent. The cost of industrial power is measured by the manufacturer not at the switchboard but at the point of utilization. In manufactured articles there is a wide variation as to the ratio which the cost of the power bears to the cost of the finished product. In many cases this ratio is not large, which points out the fact that frequently the correct application of the power is of more importance than the cost of it. By the proper design of the power plant, of the electrical system to be used, of the particular motors and controllers, etc., the product in quantity and quality can often be favorably affected to a very considerable degree.

The cost of power is made up of many items, of which the fuel cost is but one and sometimes a minor one. The interest charges, the cost of operation and the maintenance and repair items in many cases, even where a blast furnace or coke oven gas is used, make it preferable to use steam turbines instead of gas engines.

Electrical power derived from transmission systems, connected to hydroelectric stations, is being more and more used for industrial power purposes. Continuity of operation is a factor of prime importance in manufacturing establishments, and the reliability of these systems is a consideration of the first magnitude. Transmission systems are in operation which have practically no interruptions, although there are, of course, exceptions. In connection with power taken from transmission systems, the use of a steam turbine reserve, which can be thrown on the distributing system quickly, is in some cases necessary and in many cases desirable. It is not in general appreciated how quickly steam turbines may be started, synchronized and loaded. The time from the first indication of trouble on the transmission line to the condition where the turbo generators are fully loaded on the system need not be over 30 sec., starting all the machines and auxiliaries from rest. The condition of interrupted power supply is being rapidly removed.

R. P. Bolton: I think we are all under a considerable debt of gratitude, whether interested in one form of the use of power or the other, to the authors of these papers. They have some sound and fundamental facts and so far as my judgment and experience goes they are right in their general conclusions. I must controvert the statements of a previous speaker in so far as they refer to insurance on labor, on the hazardous class of which rates have now risen until they amount to nearly six per cent, in addition, to fire and boiler insurance, which thus form a not inconsiderable item of expenditure.

The question of depreciation is very often misunderstood. Depreciation is the result of the failure of maintenance, of upkeep, of repairs, and of all the other attentions that are given to machinery to effect their full purpose of prolonging its useful and economic existence. There are two kinds of depreciation, that which comes about from what is commonly known as physical decay or obsolescence, and that which is due to economic causes. I congratulate myself that my mind has been in this matter working along the same lines as Mr. Parker's, although we have been separated by the length of the State of New York from each other.

As regards the provision for depreciation, I find in Mr. Parker's paper that he has amortized depreciation at a rate of compound interest of six per cent. A preceding speaker took exception to the rate of six per cent interest upon the money invested in a plant of machinery but he did not take exception to the use of a six per cent rate on the amortization, because that had the effect of reducing the amount required for depreciation. In the table, the rate of amortization capitalized at three per cent, which is the rate you can get in most savings banks should average 4½ per cent on the total, and therefore the total in Table 2 should be increased about two per cent.

In Mr. Hibner's paper the load factor which has been assumed seems to be too high. In Table 2 on the basis of a working period of 2280 hours per year, it is 86 per cent. By Fig. 3, the actual factor is nearer 40 per cent and the cost would therefore be at least 3.5 cents per kw. hr. This reference leads to consideration of the manner in which uninformed people plunge into the establishment of power plants without knowing anything at all about the subject of load factors. In a recent case where a factory was running on a public service having a very light load and a considerable variation in the power load due to the use of elevators, the owner insisted on putting in a power plant which is so proportioned as to operate on a sixteen per cent load factor.

The use of exhausted steam, as a by-product from plants in commercial buildings, is subject to climatic conditions—the nearer you get to the North Pole the more use may be made of exhaust steam as a by-product; the nearer you are to the Equator, the less use can be made of it. Under such conditions electric demand and heat requirement do not fit together.

The percentages of the sales of live steam supplied by a public steam supply company in this city during the heating months are as follows. October, 3.2; November 7.2; December 15.5; January 25.7; February 22.6; March 20.6; April 5.2. The percentage of steam generated during the same months by a generating plant in a business building near the steam plant is as follows: October 13.4; November 12.9; December 14.8; January 15.0; February 13.9; March 16.1; April 13.73. There are other limitations of the availability and use of exhaust steam, and one which affects the question more than anything else is the load factor. In the operation of a certain generating plant in this city, I found that a kw-hr. is generated for about 6.5 lb. of coal per kw-hr. under the best conditions only for a very limited period of the day. On Sunday the consumption rises to 36 lb. of coal per kw-hr. The generators in that plant are never loaded in excess of 75 per cent of their capacity. Many operating engineers appear to be afraid to operate a unit at full capacity. I recently saw a fine 4-valve engine driving a 250 kw. unit, in a first-class hotel, the load of which at the time was approximately 90 per cent of full capacity, and as soon as that load was reached another generator of equal size was put in operation, reducing the load factor to 45 per cent. I am not against the installation of power plants where they are required, but I am against the introduction of power plants where they are not necessary, and where they are not properly and economically needed is often the place in which they are installed. The kind of engineering I hope to see developed will be that which will refuse to be tied to either side of this question, but will be willing to see the economic side of this very important matter.

Arthur Williams: It seems to me this is a question simply of kw.-hr. cost, so far as the electrical service is concerned, and of the cheapest method of obtaining it. In regard to the first two papers, bearing upon the cost of operating private plants, I am compelled to take issue with the distinguished authors—they have not placed the cost of current, at least under conditions existing in such a city as New York, at anywhere near its true value. In Mr. Hibner's paper, Table I, we have the cost of steam, and, while the details upon which my conclusions are based will be given in my notes to be published in the PROCEEDINGS, I will say that the amount allowed for heating the building with an average heating load of 62 h.p. is altogether too high. By a process of elimination—first, the correction of the investment, lowering it to $2,000, instead of $4,000, we get nearer to the facts. On this basis the annual "fixed charge" on an investment of $4,000 should be $600, but upon the more nearly correct investment estimate of $2,000 it is only $300. As to coal for heating alone the cost appears overstated. Four hundred tons (for an average of 62 boiler h.p. for the heating season) would be sufficient, which at $3.00 would cost $1200. And in the matter of labor, a fireman's wages for a full year have been charged; assuming, as here, that one would be sufficient, his wages for 30 instead of 52 weeks would be $450. Making these changes, the yearly cost of heating the building in question is about $2,000 instead of $2,705. The point may be small, the saving of $705, but it is referred to later when the cost of operating the private plant is considered. Following the same table, we find, first, rather too small an allowance. Mr. Martin admirably covered that subject. My own criticism summarized fixed charges at 15 per cent, and, making this allowance, the final result, which is shown in detail in my own comments, becomes 5.5 cents per kw-hr., instead of 2.29 cents; that is to say, under the conditions existing in New York, and using the same basis that the author used in his paper, we get the larger average cost.

In table III, we come to the question of the producer gas plant. Apparently the author uses a single unit, compounding the interest on the investment, but at a very low rate, altogether too low for that purpose. He allows simply a single engine for a very important building evidently forgetting that producer gas plants are hardly more reliable in their operation and hardly longer in life than an automobile engine, instead of a steam engine. I have changed the ratio of depreciation on the total investment to 20 per cent, giving the reasons, and in this case we again reach a total cost of 5 cents a kw-hr., instead of about 2.5 cents.

Referring to Mr. Parker's paper he again, estimates 2.63 per cent as the annual depreciation, but I do not know of any case—and I have asked several engineers if they knew of any case—where annual depreciation is actually put aside in a fund upon which interest is accumulated from year to year, and the universal answer is "No." Therefore, in my own criticism, I have taken a general depreciation rate of 7.5 per cent. Mr.

Bolton has given two causes for depreciation, obsolescence and physical life. There is a third, and that is, the moment that a competing service becomes available at a cost not exceeding the cost of operating the private plant, then the depreciation of that plant has become complete, 100 per cent, and so long, therefore, as its operation is continued, it must be apparent that operation is continued at a loss to the operator. I think, therefore, that I have not gone beyond the bounds of conservatism in taking 7.5 per cent throughout my notes, as the basis of depreciation. Finally, in going through Table I of Mr. Parker's paper—I trust he will pardon me for criticising it in detail—we find that the total cost becomes, by a process of elimination, $8,000 for operating the plant, which is 7 cents a kw-hr.

I heartily accord in Mr. Bolton's suggestion, and I am seriously of the opinion that it is a matter of very great importance to this Institute, that we should have consulting engineers who have no interest whatsoever in the outcome of their advice; that they should be called in to advise the owner as to the cost of power, taking everything into consideration, without reference, finally, to the outcome. Under the present system very largely the engineer must prepare plans and specifications, which are absolutely necessary in most cases to determine the cost and the best way of obtaining power, and if the plant is not installed, that entire expenditure of time and money is lost to the engineer. I think that this, at least in this City, is a very general practice, and in my opinion it is a wrong practice and should be changed. I have ventured to offer some suggestions on this point, which will appear in the PROCEEDINGS.

Finally in summarizing what charges should be allowed, I have taken six per cent as the allowable rate on money, on the theory, at least, that that is as little as any one would expect to get on his investment for any investment corresponding to a private plant.

Now, a word about operating costs. I think there are three points of view—that of the consulting engineer, oftentimes, that of the central station representative, and finally the exact operating cost of the plant after it has been in service some years. I have here simply one point to which I want to draw your attention—some years ago Mr. Isaac D. Parsons presented a paper in the Engineering Magazine, the February 1902, issue, in which he gave the average number of pounds of coal consumed per kw-hr., in a large number of plants. I believe there were three apartment houses, three hotels and three clubs, representing in these three classes the most difficult service in the world with which a central station in a large city must compete. I have never seen the accuracy of Mr. Parson's figures questioned, but I have seen them confirmed in many ways, of which Mr. Bolton has just given an instance. He finds they go as high as 25 lb. of coal per kw-hr. generated, including the coal required for heating. The final of the averages is 17.3 lb., and the average of all, divided by the kw-hr. required, is 15.5 lb. of coal per kw. hr. I think customarily we find in preliminary estimates from 6 to 7 lb. allowed.

In conclusion, let me give you three exact illustrations of the cost of operating private plants in this City. The details are given in my notes, and will be found of interest, because they represent very careful tests which have cost several thousand dollars. The first is a modern office building of 3,000,000 cu. ft. The admitted cost last year, from the books kept by the owners, of light and power, heat, and the elevator service, was $36,085. This is an exact statement. Central station service has been offered, under any guarantee which the owners may require, including the heating of the building, for $27,000 a year; that is, the entire element of fixed cost, which in this case becomes $9,000, may be ignored, and the central station service, plus the cost of heating the building from the boilers on the premises, is identical with the present cost of operating the plant. The second case is a modern hospital, the expenses of which admittedly ran to $24,580, with nothing allowed on the original investment of about $60,000. The authorities of the hospital have been offered a contract under which the total cost of heating, plus the cost of electric current supplied from the street, cannot exceed $22,000 a year. My third illustration, which is the most difficult of all with which to compete, is a large modern hotel—the costs here were taken from the books. The investigation was made by two engineers of note in our city, one jointly employed, and the other employed only by the owners of the hotel. The cost in this case is $41,297. 500,000 kw-hr. were made, and this item of $41,297 includes nothing but fuel, labor, removal of ashes, some repairs, etc., but nothing for interest, depreciation, taxes or insurance. They were made an offer of $40,920 as the cost of steam heating supplied from the building and electricity purchased from the street. There again the entire element of fixed charges may be waived, and yet the two costs balance each other. I think the figures given in my analysis will be found typical upon correspondingly careful investigation of the conditions that exist in practice in large buildings in such a city as New York.

Parker H. Kemble: I think all of us who have occasion to look up the costs of a private plant service, as compared with a public corporation service, should be grateful to the authors of the paper this evening for emphasizing a lot of points that are not usually clearly brought out. The points to which I wish particularly to call attention are in Mr. Hibner's paper, especially Table III. The item of profit is given at five per cent. I do not think any manufacturer will go in o business on the basis of a five per cent profit, with the anxiety and worry and chance of failure, when that profit can be obtained by the purchase of any ordinary good bond on the market. I called up a half dozen manufacturers in Brooklyn and asked them what turn over they would consider it necessary to have on $15,000, in order to make it worth while to take it up and consider it. The lowest man of the six gave a turn over of 15 per cent, on the basis of five per cent for the use of the money, giving a net profit of ten per cent, or twice the amount given in the paper. The highest man of the lot gave a turn over of 30 per cent, stating that they turned over their money on an average of ten times a year, with a profit of three per cent each time. Between these two extremes, I should say it would be safe to take 15 per cent as a matter of profit. If this is added in to the cost of power, it will bring the cost up to a little over two and three-quarter cents.

Another point, as to the amount of coal—my experience in plants of this size has shown that in the neighborhood of ten pounds of coal is a conservative figure. If that is taken into consideration with the profit matter, it will bring the cost per kw-hr. to 2.84 cents. If any expense is allowed for the time of the manager which he spends in looking after the plant, that of itself will bring the cost, irrespective of the other item, up in the neighborhood of 2.5 or 2.6. Any two of these three items added together will bring the cost of power, based on Mr. Hibner's figures, to over three cents. Any large public service corporation will be very glad to supply power to a plant such as outlined here, with a load factor as given here, for 3 cents per kw-hr. on a term contract, which is the point I want to bring out.

H. H. Edgerton: I have for the last year been paying particular attention to the cost of electric current as generated in private plants.

I have here the data as to costs in one case, that may be considered fairly typical in regard to equipment and results for equal output. The plant is of 460 kw. generator capacity:

Total engine and boiler room expenses: 1909–10		$39,894.00
Total expenses for electric service		12 809.61
Credit for exhaust steam used in heating		3,157.28
Net cost of 461,600 kw-hr.		9,652.33
Net cost per kw-hr.	2.091 cents	
Interest and depreciation, $4,600	0.997 "	
Total per kw-hr.	3.088 "	

The electric service included lighting, ventilating motors and vacuum cleaning service; also 28.4 per cent of the heating and hot water service.

The elevator service, six elevators, pumping service, ice machine, sewage evacuators and remainder of the heating and hot water services was from other than electric power sources.

The cost of fuel (pea coal) was $4.20 per ton. The division of the fuel and labor accounts was based upon a series of engine indicator cards, taken over the period of a year.

I notice that in Mr. Parker's paper that central plant current is estimated, selling price, at about 3 cents per kw-hr. In this locality that figure would not cover interest and depreciation, let alone production and distribution costs.

C. M. Ripley: If by any chance these proceedings of this evening should find their way into the hands of industrial men, and others who have the decision in their hands as to whether they shall make or buy their electricity for their new plant, I would like to have this go on record—that the Commonwealth Edison Company of Chicago of my own certain knowledge own and operate three isolated plants in the basement of buildings. If industrial plant owners, managers and engineers need any further encouragement regarding the earnings of an isolated electric plant I will say that the Commonwealth Edison Company is glad to pocket the income from such, even after paying a fancy rental for the basement space occupied. Some of these plants are equipped with Corliss engines and others with high speed engines; the owners of industrial plants can likewise depend on and profit by similar apparatus designed by the same manufacturers.

H. W. Peck: At the present time, with men designated as engineers in the foreground of nearly every large economic analysis, more papers of the general character of the one presented by Mr. Parker to-night should be given before the engineering societies. Aside from the subject of railroading, there have been very few such papers—too few. We should have in our TRANSACTIONS, for example, an analysis of the principles of depreciation corresponding to Dr. Alexander Humphrey's classic before the American Gas Institute. I regard Mr. Parker's paper as a valuable contribution to our proceedings, outlining, briefly and clearly, the principles appertaining to a certain detail of everyday engineering work. Mr. Hibner's paper is valuable, also, as it discusses a subject which is of great moment to a large number of engineers; and while in most of the individual cases industrial plants are relatively of small importance, the sum total of them amounts to an exceedingly great figure, and the amount of engineering work being expended on them is very great.

Referring to Mr. Parker's paper, certain parts might properly, it seems to me, have been elaborated a little more. Other methods of providing for amortization can properly be mentioned, as, for instance:

1. A yearly sum equal to the investment, divided by the number of years' expected life, should be set aside annually, allowing the variable earnings of this fund to be added to the other earnings of the company.

2. A variable yearly sum, equal to a fixed per cent of the decreasing back value of the plant, may be set aside; for example, 10 per cent of the full value at the end of the first year, 10 per cent of the remaining value at the end of the second, year and so on. This method would never completely amortize the plant, but would more nearly represent its actual depreciation in value, and leave a relatively small amount to be charged off in one sum at the end of its natural life, or, indeed, somewhat earlier.

My own preference is in favor of the first method, although the choice of methods may very reasonably differ for different classes of business and different financial conditions.

Inadequacy should properly be mentioned with obsolescence, as in general the same considerations hold good for both conditions. Similarly, ***business risk*** is an element of ***fair profit***, though not always associated in one's mind.

In certain points I do not agree with Mr. Parker. I would call attention to the fact that the depreciation rate on certain details, considered by themselves, is not correct when they are considered as part of a plant; for example, a building which might be in excellent condition after 50 years, would, in all probability, not be useful that length of time, nor for a period any longer than the life of the equipment in it. I have in mind an expensive brick chimney and engine room which was discarded in four years' time to make way for a larger one required by increase in the business requirements. In this case the matter of inadequacy would have required a 25 per cent depreciation rate instead of a 2 per cent, which might have been allowed from the consideration that the building would be in fair state of preservation for 50 years. Of course, if this condition had been anticipated, a chimney and engine room of larger capacity would have been installed originally, so that I am not arguing for an amortization rate of 25 per cent, but simply wish to mention one of a number of illustrations of the fact that inadequacy is very likely to be the consideration which will determine the proper sinking fund.

I emphatically disagree with Mr. Parker's statement that "obsolescence, therefore, has essentially no existence for private power plants, even under stress of competition." If I purchase a plant to furnish power to operate my factory, finance it on a 20-year basis, and in five years' time improved equipment can be purchased with double the efficiency of my apparatus, a new competitor will be able to undersell me by an annual amount equal to one-half the power cost. I then have to choose between the loss of one-half the power cost annually, or the unamortized part of my plant, less its sale value. This seems to me very clearly to be the case, in fact, Mr. Parker practically admits it in a following paragraph.

The sale value of the old plant should, of course, be added to the sinking fund and be credited to the new equipment.

The charge of $2,000 for supervision is proper, of course, regardless of the salary actually paid for supervision, unless here again the marginal principle applies in apportioning the time of the superintendent, that is, that a sacrifice of 20 per cent of his time would not sacrifice 20 per cent of the profit of the business.

Under the subject *Fair profit*, it should be noted that items of necessity do not have to carry their own burden of profit; for example, an ordinary business cannot be carried on without artificial heat in the winter. The total cost of heating must be carried by the profit-making parts of the business, assuming that heat cannot be purchased from a heating company. Thus the various elements making up the cost of heat must be deducted from the corresponding elements making up the cost of combined heat and power before figuring the actual cost of the power alone. This is illustrated well in Mr. Hibner's paper except, possibly, for the considerations following.

I have observed that if 100 tons of coal per month are required for heating a building, and if 100 tons are required for power alone, it is assumed that 100 tons, or possibly 110 tons, to allow for loss in the engine, will be sufficient for both heat and power. Where the requirements so nearly balance this is manifestly not the case, for the heating requirements are distributed throughout the 24 hr. of the day, with a marked peak early in the morning before the business part of the plant begins operation. The power requirements, however, are limited to from 8 to 10 hr. a day, with the peak usually during the warmer parts of the day, or during the late afternoon, just before shutting down the factory, when it is permissible to allow the temperature to drop slightly. This means that the coal for combined heat and power may easily amount to from 150 to 175 per cent of the coal required for either purpose alone.

I do not like Mr. Hibner's use of the expression "load factor" with the limitation of ten hours. I think it is very generally agreed that load factor should be limited to daily, monthly, or annual load factor.

John H. Norris: The following examples of installations of gas engine costs of operation are presented to show the economy that can be obtained even down to small sizes when using the gas engine for power purposes. I have selected a few typical plants running on various fuels. Owing to the fact that the cost for buildings or rent for space varies so much, I have not included in my costs hereafter given any allowance for said buildings or space occupied by the installations.

Plant No. 1 is a 50-h.p. 3-cylinder gas engine direct-connected to a 125-volt direct current generator with a speed of 275 rev. per min. running on natural gas and furnishing an 11-hr. service 300 days per year.

The load on this plant is 15 kw.

Cost installed	$3,500.00
Interest and depreciation	$350.00
Repairs and supplies	175.00
Labor per year	900.00
Total operating cost, exclusive of fuel	$1425.00
Gas bill for year	315.56
Total yearly charge	$1740.56
Total kw-hr. for year	49,500
Cost per kw-hr	3½ cents.

Plant No. 2 is a 25-h.p. engine belted to a 15-kw. generator and one 20-h.p. engine belted to a 12-kw. generator running on natural gas and furnishing light and power running at approximately full load; service 16 hr. per day 365 days per year.

Cost installed, $4,200.

Interest and depreciation	$420.00
Repairs and supplies	210.00
Labor per year	700.00
Total operating cost, exclusive of fuel	$1330.00
Gas bill for year	1270.18
Total yearly charge	$2600.18
Total kw-hr. for year	128,480
Cost per kw-hr	2.02 cents.

Plant No. 3 consists of one 65 and one 30-h.p. gas engine furnishing power for a manufacturing establishment running on illuminating gas at 80 cents per 1,000 ft.

Cost installed, $4,375.

Interest and depreciation	$437.50
Repairs and supplies	220.00
Labor per year	360.00
Total operating cost, exclusive of fuel	$1017.50
Gas bill for year (80c. gas)	3279.00
Total yearly charge	$4296.50
Total h.p. hr. for year	228,000
Cost per h.p. hr	1.89 cents.

Plant No. 4 consists of one 100-kw. and one 65-kw. direct-current sets, operated by gas engines running on city gas at 65 cents per 1,000 ft. 11-hr. service.

Cost installed, $12,300.

Interest and depreciation	$1230.00	
Supplies and repairs	600.00	
Labor per year	2000.00	$3830.00
Cost of fuel per kw-hr	1.6	
Operating charges	0.7	
	2.3 cents per kw-hr.	

Plant No. 5 consists of two 75-kw. and two 65-kw. direct-current generating sets operated by gas engines and running on city gas at 65 cents per 1,000 cu. ft.

Cost installed, $23,000.

Interest and depreciation	$2300.00	
Supplies and repairs	1150.00	
Labor per year	3300.00	$6750.00
Fuel cost per kw-hr	1.6	
Operating charges	0.3	
	1.9 cent per kw-hr.	

Plant No. 6 consists of one 40-h.p. and two 18-kw. gasoline engines direct current sets furnishing light and power to a country estate.

Cost installed, $9,580.

Interest and depreciation	$958.00	
Supplies and repairs	480.00	
Labor per year	1500.00	$2938.00
Cost of fuel per kw-hr	2.025	
Operating charges	1.29	
	3.315 cents per kw-hr.	

Plant No. 7 consists of one 15-kw. gasoline engine direct-current set used for lighting service in connection with storage batteries.

Cost installed, $2,500.

Interest and depreciation	$250.00	
Supplies and repairs	140.00	
Labor per year	400.00	$790.00
Cost of fuel per kw-hr	2.025	
Operating charges	1.78	
	3.805 cents per kw-hr.	

Plant No. 8 consists of a 35-h.p. anthracite producer, 28-h.p., 2-cylinder vertical gas engine, 24-hr. service.

Belted to an 18-kw. generator.

Furnishing light and power.

Average load, 10 kw.

Fuel, anthracite pea coal at $4 per ton.

Cost installed, $3,000.

Interest and depreciation	$300.00	
Supplies and repairs	150.00	
Labor per year	500.00	$950.00
Cost of fuel per kw.at 4.00 per net ton	0.3	
Operating charges	0.61	
	0.91 cents per kw-hr.	

Plant No. 9 consists of one 300-h.p. anthracite producer, suction type, furnishing gas for two 100-kw. Allis-Chalmers generators of 60-cycle three-phase, 2300 volts, running in parallel and operated by two vertical gas engines. Fuel, pea anthracite at $4.00 per ton, 24-hour service.

Cost installed, $22,000.

Interest and depreciation	$2200.00	
Supplies and repairs	1100.00	
Labor per year	2400.00	$5700.00
Cost of fuel per kw-hr	0.3	
Operating charges	0.4	
	0.7 cent per kw-hr.	

Plant No. 10 consists of one 400-h.p. double-acting tandem horizontal engine running on producer gas furnished by two 200-h.p. anthracite suction producers driving flour mill by rope drive and grinding a barrel of flour for 8 lb. of coal

Fuel, used No. 1 buckwheat coal.
24-hour service.
Cost installed, **$38,000.**

Interest and depreciation	$3800.00	
Supplies and repairs	1900.00	
Labor per year	3000.00	$8700.00
Fuel cost at 7.00 per ton	0.42	
Operating charges	0.3	
	0.72 cent per b.h.p.-hr.	

Plant No. 11 consists of 400-h.p. double-acting tandem horizontal engine direct current 2,200-ton ammonia compressor.

Twenty-four-hr. service and giving 30 tons of refrigeration per net ton of coal, coal being Illinois slack, carrying 38 per cent volatile matter and averaging 10,300 B.t.u. per lb.

Cost installed, **$44,000.00.**

Interest and depreciation	$4000.00	
Supplies and repairs	2000.00	
Labor per year	4500.00	$10,500.00
Cost of fuel (coal) per h.p	0.1	
Operating charges	0.361	
	0.461 cent per b.h.p.	

Plant No. 12 consists of a 300-h.p. anthracite suction producer driving a four-cylinder vertical engine direct connected to a 200-kw. direct-current generator furnishing power and light.

Cost installed, **$18,000.**

Interest and depreciation	$1800.00	
Supplies and repairs	900.00	
Labor per year	1500.00	$4200.00

Fuel used, No. 1 buckwheat; cost per ton, $4.00 delivered.

Cost of fuel per kw-hr	0.3
Operating charges	0.63
	0.93 cent per kw-hr.

I have a record of a three weeks' run on this plant, in which the following figures may be of interest:

Total kw-hr. furnished	19,368
Elapsed time	480 hours
Per cent running time	36 per cent
Per cent shut down time	64 per cent
Average kw	113.85
Per cent of full load	56.9
Coal per kw-hr., including all standby losses	2.36 lb.

I have also a record of a run of one week in which the average kilowatts were 87.28.

Per cent of full load	43.6
Coal per kw-hr	3.46 lb.
Per cent of time running	37.2 per cent
Per cent of time shut down	62.8 per cent

In these two runs there has been no attempt to meet test conditions. There are simply the reading of the instruments and the actual amount of coal supplied to the producer during the time specified.

Plant No. 13 consists of a 150-h.p. anthracite suction producer, furnishing fuel to a 150-h.p. three-cyclinder vertical engine direct connected to a 100-kw. direct-current generator furnishing power and light to a manufacturing establishment. Eleven-hr. service. Fuel, pea anthracite at $4.00 per ton.

Cost installed, $9600

Interest and depreciation	$960.00	
Supplies and repairs	480.00	
Labor per year	750.00	$2190.00
Cost of fuel per kw-hr	0.3	
Operating charges	0.66	
	0.96 cent per kw-hr.	

Plant No. 14 consists of three 200-h.p. producers, furnishing fuel to one 600-h.p. double-acting tandem gas engine direct connected to 400-kw. alternating current generator, 60-cycle, three-phase 600-volt, furnishing power for cement mill.

Fuel, Texas lignite, carrying 8000 B.t.u. per lb. and costing $1.50 per net ton delivered. 24-hr. service.

Cost installed, $40,000.

Interest and depreciation	$4000.00	
Supplies and repairs	2000.00	
Labor per year	3200.00	$9200.00
Cost of fuel per kw-hr	0.169	
Operating charges	0.32	
	0.489 cent per kw-hr.	

Plant No. 15 consists of one 150-h.p. suction producer furnishing fuel to one 150-h.p. vertical three-cylinder gas engine direct connected to a 100-kw. generator furnishing light and power.

Cost installed, $9600.

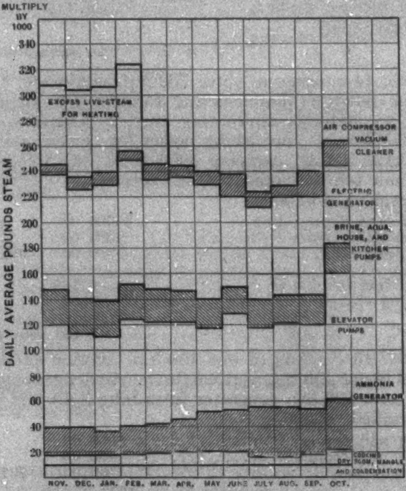
Interest and depreciation	$960.00	
Supplies and repairs	480.00	
Labor per year	1700.00	$3140.00
Cost of fuel per kw-hr	0.17	
Cost of operating	0.4	
	0.60 cent per kw-hr.	

In connection with this plant, I have a record of a 38 days' run which is as follows:

Duration of run	912 hr.
Time shut down	75 hr.
Per cent time running	91.75 per cent
Per cent time shut down	8.25 per cent
Total kw-hrs	38,353
Total lignite supplied to producer	196,520 lb.
Consumption per kw-hr	5.12
Cost of fuel per kw-hr	0.42 cent
Operating charges, as above	0.43 cent
Cost per kw-hr. at 40 per cent load	0.85 cent

Referring to the statement of Mr. Williams, that the gas producer is a very unreliable piece of apparatus, I would like to state that as a matter of fact the depreciation of a gas producer properly run is less than that of a steam boiler plant, and the gas producer of to-day is a very satisfactory and reliable power generator.

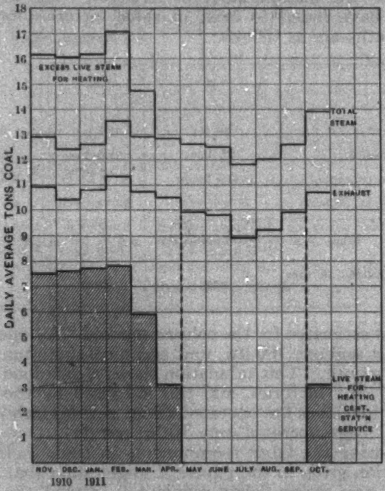
Richard H. Tillman: The paper by Mr. Parker on "Fixed Costs" will more than likely bring out sufficient discussion to have its title more appropriately termed "Variable Fixed Costs". Notwithstanding this fact, however, the paper represents the cold facts so plainly that it will be hard to refute the claims made therein. This paper will be the means of bringing out many ideas and will be the base of much good work in industrial engineering.



CURVE No. 1.—Showing operating conditions. Typical hotel plant Steam distribution

One item of fixed costs entering into an industrial power plant which has not been brought out plainly in the paper is what we might term "first interest and depreciation costs". When a new factory is to be located the first large expense is made in the power plant equipment. This equipment is usually purchased to supply the total needs of the complete industry and sometimes, contemplated additions to the factory. It is usually several months from the time the power equipment is purchased before any factory is operated at its full capacity. It is evident that the greater part of the fixed costs begins when the plant is first purchased.

The amount of fixed costs that can be charged against plants in an unfinished condition will, of course, depend on the size and type of construction and machinery used, or the time that portion of the plant is idle. In the case of purchased power, where the power rates are based upon the fixed costs on the actual power demand metered, the first fixed costs on a new industry will not be so heavy.



CURVE NO. 2.—Showing operating conditions. Typical hotel plant Coal consumption

In the paper entitled "The cost of Industrial Power" by Mr. Hibner, we find some very interesting as well as valuable points. Most of the figures presented in this paper can certainly be verified by figures from different locations. There is one question which I would like to ask concerning Table II of the paper.

Under the head line "Operating Costs of Power Plants" there are two items, namely "Banking" and "Night heating".

I would like to ask Mr. Hibner what is the difference between these two items, and how are they arrived at.

As mentioned in Mr. Hibner's paper, we find that the actual industrial power plant costs are very indefinite. Also estimates on the necessary capacity for industrial plants have been found to more than double the actual requirements when the plant was put in operation. I have known of instances where the consumption in kilowatt hours of an industrial establishment was estimated by considering the total rating capacity of the boilers for the total time the factory was operated. To demonstrate this let us consider one of the many industries in which Baltimore leads—the manufacturer of fertilizer. The actual costs which we have found to exist in three factories for the past twelve months are as follows:

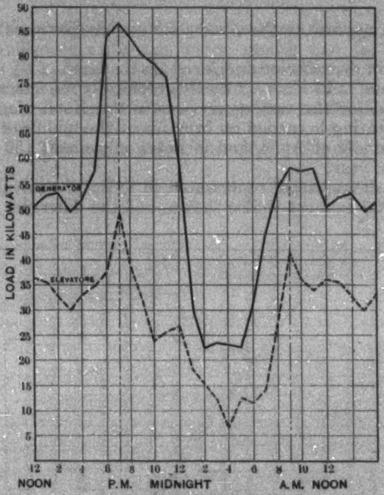
	" A "	" B "	" C "
Connected load	198 h.p.	170 h.p.	350 h.p.
Maximum demand	75 kw.	91.5 kw.	92.5 kw.
Av. monthly consumption	14410 kw-hr.	19118 kw-hr.	10592 kw-hr.
Load factor (10 hr. 26 days)	74 per cent	80.4 per cent	44 per cent
Motor capacities	1–50 h.p.; 1–40 h.p.; 1–30 h.p.; 3–20 h.p.; 1–15 h.p.; 1–3 h.p.;	1–100 h.p. 3–20 h.p. 1–10 h.p.	5–40 h.p.; 1–35 h.p.; 1–20 h.p.; 2–15 h.p.; 5–10 h.p.; 2–7½ h.p.
Approximate output in tons per month	3500	6000	3500

The plant estimated for the column marked " A " included one 200-kw. unit and one 100-kw. unit and a consumption of 35,000 kw-hr. per month. This tabulation shows a high load factor on " A " and " B " factories, and this is caused by the fact that part of the machines are operated 22 hr. per day, while those in factory " C " are operated only 10 hr. per day.

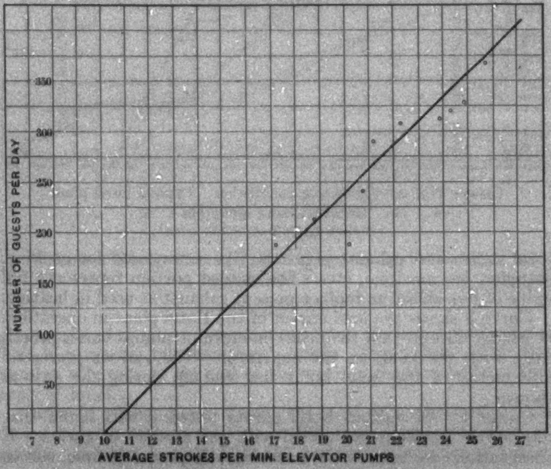
In comparing the labor requirements in these factories with the tabulation given in the papers, I might state that in no one of them is any expert labor required to attend the electrical equipment. An oiler passes through the factory about twice during the day and takes note of the bearings, spending the remainder of the time at other work.

There has but lately come to my notice a forceful instance of how a plant may be over burdened with fixed as well as operating costs, by a biased engineer. I have prepared curves to illustrate how this could have been easily obviated by careful investigation and comparison of plants of similar type; also how the costs entering into the total expense of a plant can be separated.

This plant consists of 525 kw. in generating units and the maximum electrical demand is 90 kw. It is not necessary to comment on the fixed costs of such a plant. By the use of a



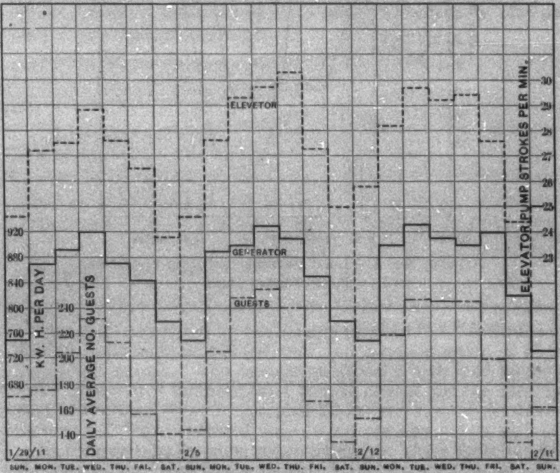
CURVE No. 3.—Load showing operating conditions
Typical hotel plant



CURVE No. 4.—Operating conditions. Typical hotel plant elevator pumps condensing apparatus the steam for various services was determined.

The steam distribution is figured on the basis of 8½ lb. steam per lb. of coal, and Curve 1 shows graphically the exact amount of coal used for the various services in the Hotel plant. This far south heating is carried on from about the middle of October until the middle of April, and includes only about 150 days for heating per year.

Curve 2 shows steam represented in terms of equivalent coal value. Total exhaust is also shown, and the difference between total steam and exhaust gives the live steam used for cooking, mangles, ice machine, etc. The shaded portion represents full value of live steam to replace present exhaust as used in heating.

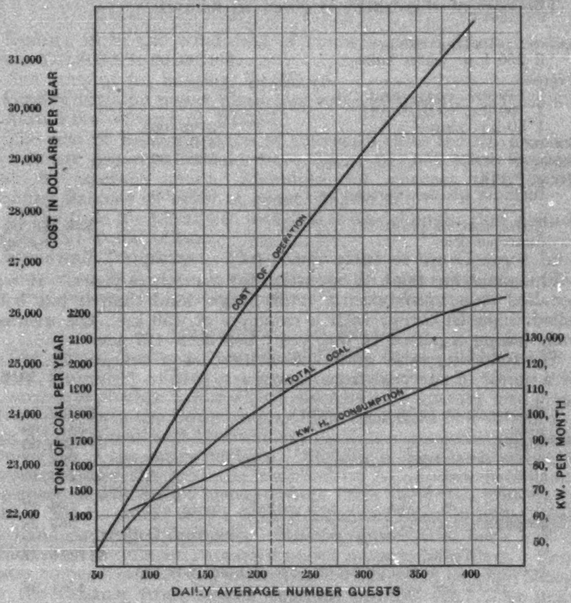


CURVE NO. 5.—Operating conditions. Typical hotel plant Generator and elevators

Curve 3 shows the load curves of the Hotel plant in operation. It will be noticed that the peaks on elevator pumps varies practically with the peak on the generator. The various power requirements of the hotel holds the load up during the day as shown.

Curve 4. In various hotel plants tested it was found that the power requirements varied with the number of guests. If observations are taken over a considerable period of time, curves can be plotted which establish the working law by which the power requirements for any given month can be calculated when the total average number of guests is known. It is to be noted that when the number of guests is reduced to zero that the pumps are still doing work. This is due to the help, freight elevator, etc.

Curve 5. This curve shows how closely the operation of the generator and elevator pump depend upon the number of guests. This is a typical business man's hotel. The falling off in the number of guests at the end of the week is characteristic of this type of hotel.



CURVE No. 6.—Cost of operation, central station service
Typical hotel plant

Curve 6. This curve shows the cost of operation. This factor bears a certain relation to the total average number of guests. It is to be noted that the greater the number of guests the less the variation in cost for a given increase in number, showing that a high load factor for guests is also a profitable thing for a hotel.

W. S. Timmis: The power plant installed at 435 East 24th St. consists of three 250-h.p. water tube boilers, two 150-kw. direct-connected generators with compound engines, one 100-kw. generator, compound engine, and one 50-kw. direct-connected generator, simple engine. Also two 7½-kw. balancer sets.

The cost of this outfit is given as follows:

Boilers, including setting.		
3 250 h.p. water tube	$11190.00	
Engines.		
2 150-kw. compound		
1 100-kw. compound		
1 50-kw. simple	12190.00	
Generators	6100.00	
Balanced draft	2325.00	
Steam Fitting.		
Includes all auxiliaries	6378.00	
Total cost of plant		$38,183.00
Cost per kw		84.85

This plant has been in operation for over three years. It was installed to accommodate a much larger load than it has been called upon to carry; with a capacity of 450 kw., the average load, taking a period of one year, has been 127 kw.

The following table gives the actual cost of running the plant for a period of one year from January 1, 1910 to January 1, 1911.

Wages (cost to run one year)	$5233.84
Coal	4817.69
Water	360.00
Ashes (removed)	223.24
Oil and waste	164.40
Supplies (packing, sheet rubber, pump valves, soda-ash, boiler handhole gaskets, piping, etc.)	159.27
Repairs	263.28
Total	$11221.72
Interest and depreciation on cost of plant $38,183 at 12 per cent	4581.96
	$15803.68

Kw. metered 381,500.
Cost per kw. $0.0294 without interest and depreciation.
Cost per kw. $0.0412 including interest and depreciation.

During the year there were 722 hr. overtime at time-and-half per hr.:

Assistant engineer	75c. per hr.
Fireman	56c. per hr.
Sundays and holidays (5 days and 6 hr.), which makes a total of	$1024.32*

*This item is included in the total amount under wages.

The above figures include the cost of heating the building, the value of which is estimated as follows:

Coal 585 tons	$1949.75
Two firemen 30 weeks, $15 each	900.00
Part time of chief engineer	500.00
Water	30.00
Removal of ashes	90.00
Interest and depreciation on boilers 250 h.p. and distributing panels, $4740.00 at 12 per cent	568.00
Total	$4037.75

Deduct from the total cost of running power plant for one year, $15,803.68.

The amount for heating, $4,037.75.

Cost of running power plant less value of heating, $11,765.93.

Actual cost of current, 0.0323.

The cost of Edison service at wholesale rates for the amount of current generated would have been, $17,660.16 as against cost to operate plant, including all charges $11,765.93. Leaving balance in favor of plant, $5,904.23.

At the time the plant was installed it was thought that a much larger load would obtain.

Stonewall Tompkins: The power plant of the Coney Island & Brooklyn R.R. Co., is not one of the large ones, but may, for this reason, be not less interesting for discussion.

DESCRIPTION OF PLANT

The power house is located at Ninth Street and Gowanus Canal, Brooklyn. Coal is delivered in lighters from which it is hoisted into storage tanks which discharge by gravity into a car which runs into the boiler room. The coal used is a mixture of No. 3 buckwheat and bituminous, the latter constituting about one-eighth of the entire mixture. Stoking is done by hand. Air pressure under the grates is supplied by steam-driven blowers, the speed of which may be regulated. The burnt gases discharge into a 200-ft. stack, and a nearly balanced draft is maintained by hand controlled dampers. Shaking grates (the back half of which may be dumped) are used under water tube boilers. Feed water comes from the city mains, and is heated in an open heater by the exhaust from blower engines, pumps, etc. The main generators are vertical shaft turbine-driven alternators, and the exciters are horizontal turbine-driven. The turbines exhaust into barometric condensers, having motor-driven centrifugal pumps, and steam-driven flywheel dry vacuum pumps. There are steam-driven pumps for the step bearings, and for the oil-pressure governors of the turbines. The plant operates twenty-four hr. per day every day in the year. There are two daily peaks in the load, the greater one occurring about 6:00 p.m. and the lesser about 8:30 a.m. The effect of the seasons is to make the load heavy in hot weather on account of great traffic, also heavy again in cold weather on account of extra current used in heating the cars, and in overcoming bad track conditions of snow, sleet, etc.

Each car of coal is weighed as it enters the boiler room. Water is measured by meter on the city supply, (and the cost of water herein given covers not only all evaporated in boilers, but all other water used about the plant). The electric energy is metered at the switchboard, but a small portion of this is afterwards used to drive the circulating pump motors, and is not separately metered. It has, however, been estimated at 3 per cent of the total output of the plant, and therefore the total output of the power house as herein given is 3 per cent less than the actual metered amount.

LIST OF EQUIPMENT

2 2,000-kw. three-phase turbines.
2 75-kw. exciters.
2 Barometric condensers.
2 Motor-driven centrifugal pumps.
2 Steam-driven dry vacuum pumps.
2 Steam-driven step bearing pumps.
2 Steam-driven pumps for oil pressure governors.
2 Steam-driven blower engines.
2 Steam-driven boiler feed pumps.
6 600-h.p. water tube boilers.
Boiler pressure, 175 lb.
Primary voltage, 11,000 volts.

It should be noted that the expenses for power herein shown do not include the following items:

Interest on investment.
Depreciation.
Taxes.
Insurance.

Nor do they include anything for the pro rata expenses of the officials of the company:

Power House. Total energy (11,000 volts three-phase) measured at power house switchboard, and delivered to cables for transmission to sub-stations.......................... 26,122,312 kw-hr.

POWER HOUSE EXPENSES

Fuel, (41,517 gross tons)	$81,170.06
Labor	51,617.97
Water	10,503.53
Lubricants	1,724.14
Supplies and expenses	4,510.78
Repairs of steam machinery	9,757.44
Repairs of electric machinery	2,077.59
	$161,361.51

Cost per kw-hr. alternating current. $0.006084
Cost of coal per gross ton....... 1.955
Coal per kw-hr.................. 3.5662 lb.

Sub-stations. Total energy (575 volts direct current) measured at substation switchboards, and delivered to feeders.................. 23,065,393 kw-hr.

SUBSTATION EXPENSES

Labor	$14,053.56
Supplies and expenses	203.77
Repairs in stations	472.59
Repairs to ducts	874.77
Repairs to 11,000 volt cables	992.04
Total substation expenses	$16,596.73
Add total power house costs	161,361.51
	$177,958.24
Cost per kw-hr. delivered to the direct current feeders	$0.007715

F. G. Gasche (by letter): This paper deals with a subject so timely and important that I feel impelled to urge its widest distribution. The author has made reference to the small plants particularly, but the principles are frequently of general application, and it seems that some of the larger power plants could have been studied to great advantage by methods proposed by Mr. Parker.

The observations concerning " investment " and " interest " cannot be emphasized too strongly, as many additional responsibilities are assumed as soon as a sum of money is appropriated for a given power plant.

The element of " depreciation " is unquestionably subject to variant views, but the evidence of past experience of many engineers would indicate that depreciation " rates " are generally too low and this for a reason quite foreign to the physical permanence of an engine or other part of a power plant equipment. I refer particularly to the rapid changes in method or process which characterize an industry, thus making a power plant obsolete so far as its primary functions are concerned. This may be illustrated more clearly, but I would urge that many industrial power plant elements should not be credited with a useful existence of more than ten years since they may be wholly unsuitable for the purposes of a new business. To illustrate, twenty years ago the simple, vertical, long crosshead type of blowing engine was installed at a group of four blast furnaces. About eight years after, half the group of engines was replaced by larger machines with large steam cylinders, so as to operate them as disconnected compound units. In fifteen years time from the start, they were practically superseded by improved forms of compound engines. About two years ago the new engines were " assisted " by gas driven blowing engines using blast furnace gas, with the implied intention of displacing all steam blowing engines. Now arises the " specter " of the turbine driven turbine blower to set all finance of the power plant " agog " in view of the possibilities. The point I wish to emphasize from this is that fundamental changes in the iron and steel business imposed these changes and not the mere " obsolescence " of the elements of the power plant. Nevertheless, they had a short life. Other lines of industry, not excepting the business of furnishing electric current, have exhibited similar crises in their development.

There is another element of growing importance in the finance of power plant investments which may for the want of a better name, be called "insurance on reliability". This consists of the aggregate of annual charge that should be set against the gross earnings by virtue of the presence of "spare units", or duplicate equipment of boilers or other apparatus, the purpose of which is to insure uninterrupted service of the plant for any loads that may be assumed. In some cases a full examination of this "reliability" charge indicates that a mistake can be made in the installation of prime-movers of excessively large capacity.

For many lines of industry there are periods of enforced idleness so far as a part of the power plant is concerned, and it is somewhat surprising to note their influence on the power plant finance since the accumulation of interest and similar charges is continuous.

The ultimate result of the examination of the finance of power plant investments will consist in the statement of a series of numerical items affecting the final numerical values of net returns on the investment. Consequently any consideration involved in such analysis, must be capable of measurement in terms of numerical dollars.

A continuance of the study of the subject as illustrated by the paper of Mr. Parker, will ultimately lead to a consensus of opinion as to the nature of the elements entering the problem, and to a knowledge of the laws controlling their effects as illustrated by the "marginal principle" proposed by Mr. Parker. We may hope for the ultimate development of the algebra of finance calculations as a necessary preliminary to proper numerical substitution. Finally, and most important, the selection of interest rates, amortization rates, and all similar items must be established in accordance with legal and geographical restrictions, to say nothing of the attitude of banking interests whose ruling would be almost a finality.

Bearing on this, there is great danger in applying a greater interest rate to the formulas in appendix B, than banking concerns would allow for such loans bearing interest compounded semiannually. This would seem to limit the interest to 3 per cent or at the most, to 3½ per cent, corresponding to the usual savings bank allowance. Certainly the amortization period cannot be calculated with the formulas of appendix B, with the legal rates of interest for time loans applied.

William B. Jackson (by letter): There is no doubt that the cost of power as generated by isolated plants is usually underestimated by those having such plants in charge. This is likely to be due to a combination of several causes.

It is usually difficult for the management of a mill or factory to fairly recognize charges that should be made against power generation on account of the work required of the purchasing department of the mill and on account of the proportion of the effective usefulness of the management diverted from the regular business of the company. The former may be of minor importance, but it is likely not to be negligible, while the latter may be of material importance since it diverts the attention of the management from the prime business of the property. An effective management should have sufficient work in developing the business of the company to fully absorb all of its effective strength and resources.

Likewise, it is almost impossible to obtain recognition of extraordinary costs that are incident to an isolated plant, such as those occasioned by uncertainty of coal supply as regards cost, quality and quantity, expense on account of labor strikes, and the uncertainties of the labor market, the occurrence of accidents occasioning extraordinary expense not covered by ordinary forms of insurance, and other like expenses.

If the management costs and the costs occasioned by extraordinary occurrences are fairly taken into account, they are likely to prove a very respectable proportion of the total cost of power generation, and in many instances, I estimate they will be 10 per cent or more of this cost.

I find that the average mill owner who is operating his own power plant, has little definite knowledge of the actual amount of power that he is using. There is the same tendency to over-power a mill when driven by a steam engine as is so noticeable when electric motors are used, and there is an inclination to consider the full rated horse power of the engine as representing the power requirements of the mill. Also, there is usually small appreciation of the comparatively low load factor incident to the operation of most factories or mills, so it is natural that there should be a tendency to over-rate the amount of power being used, and therefore, to under estimate the cost per unit of power.

It is an extraordinary superintendent of a factory steam plant who will seriously combat such misconceptions regarding the cost of the output of his plant, since both pride and policy lead him to accept the lowest plausible figure that can be arrived at as the cost of the output of his department. In many cases, there is honest belief in unreasonably low figures for cost of power. This may be illustrated by a case wherein the management of a mill fully believed they were producing twenty-four hour power for 310 days in a year at less than $20 per indicated h.p. yr., that is, per 7440 h.p.-hr., and they had figures to substantiate this belief. By the results of a carefully organized and conducted test of the plant, with an accompanying complete study of the conditions, they were clearly shown and fully convinced that they must add 50 per cent to the cost they had theretofore accepted as a true one. This was an unusually well-conducted isolated plant operating a large cross-compound condensing engine.

A serious difficulty in the way of obtaining a clear conception of the relative costs of industrial power by different isolated plants, is the uncertainty as to what are the relative conditions under which the power plants are operating. If intelligent comparisons are to be made, it is not sufficient to know the cost per h.p-hr., or per h.p-yr. These mean little in themselves except as related to the plant to which they refer, and under particular load conditions. It is impossible to intelligently compare costs or to obtain a true understanding of what the costs for power really mean without having a knowledge of the costs per h.p-hr., subdivided so as to show the costs of fuel, for oil and waste, for repairs, for boiler room labor, for engine room labor, for insurance and taxes, for management expense, for unforeseen contingencies, for depreciation and for interest, and the basis upon which the two latter are determined must be known. In addition to a knowledge of these costs, an understanding of the operating conditions must be had, including the cost and quality of fuel, the cost of water, how many hr. per day the plant runs and how many days in the year, the variations in load during individual days and from day to day, the size of the plant, the ratio of the average load to the maximum load of the plant, and the ratio of the maximum load to the economic full load capacity of the boiler plant and of the engine plant.

With these data, the relative performance of the plants as affected by their construction and operation may be determined.

The above seems a formidable array, but any comparison of plant costs becomes less and less valuable as the subdivisions are omitted, until the point is reached where merely the total cost per h.p-hr., and the size of the engine are known, when the data becomes substantially worthless for comparative purposes. It is thus seen that published costs of power, unless accompanied by very considerable data, cannot be valuable as giving a true understanding of the cost of power. As an illustration of this, had the load factor in the plant heretofore referred to been half as good as it was, the cost per h.p-yr. 7440 hr. would have been 50 per cent greater than it was found to be. This is assuming the same running hours for the plant and the same uniformity of load during individual days.

R. Tschentscher (by letter): The subject discussed by Mr. Parker treats of a matter concerning which there exists considerable misinformation and a material lack of appreciation of the various details. It can truely be said that the proper appreciation of " fixed costs " is decidedly limited among engineers and business men. The paper specifies a reference to industrial power plants but it is very probable that the remarks made and the subject treated apply to all power plants, as it appears to the writer manifestly illogical to assign factors governing a return value on the dollar invested in one plant materially different from those for another plant. In arriving at the cost of power, the same elements are in evidence as exist in arriving at the cost of any other commodity, be this commodity overalls or transportation. The readily determinable operating costs—fuel, upkeep, operating labor, etc.—are too frequently given serious consideration to the exclusion of the consideration of the really more important elements comprising fixed charges. It is frequently factors comprising " fixed costs " which govern the success or failure of an enterprise, be it the generation of power or the handling of transportation. The proper determination of these fixed charges is much more difficult of analysis than that of the operating costs and leads to greater erroneous deductions.

In connection with the matter of " investment " it must be appreciated that the investment charge may vary from year to year, *i.e.*, for example, a 10,000 kw. plant in a certain locality may represent a total investment charge (equipment, land, buildings, engineering, erection, etc.) of $1,000,000. Within five years, the value of land may have increased 25 per cent. Building material and labor may have increased a like amount so that replacement of the building would be increased 25 per cent. Cost of copper, iron and other raw material may have so increased that to reproduce the plant would require an investment of $1,250,000. This, of course, would increase the total amount of taxes, interest, depreciation, etc., which must be considered. The writer believes that the consideration of this feature must be given due weight in the determination of the installation to be made. It is possible that the appreciation of the investment may be such that the fixed charges due to this appreciation may be so great as to offset the gain in operating cost of one installation over that of a less expensive installation.

The definition of depreciation given by Mr. Parker is not as fully appreciated as it should be. The determination of the proper depreciation period is an extremely difficult one and as this item is the largest of those constituting " fixed charges " it deserves the greatest consideration. For example, what is this period for (*a*)—a high grade high pressure steam turbine plant, (*b*)—a blast furnace gas engine plant, each installed during 1910. The depreciation period will depend to a considerable extent on the number of spare units (making investment high but repairs and actual depreciation less) and also upon the operating time of each unit. In other words, the actual depreciation period (considering this period in this connection as the " worn-out period ") will be longer in a plant where the various units are operated on a 10-hour basis than where they are operated on a seven-day-per-week 24-hour basis. The question of the efficiency of the operating labor is also a determining factor of the question of depreciation. A plant may be located where, either because of ignorance on the part of the management or on account of local considerations, the equipment is handled by inefficient operatives. This not only affects operating costs but also the depreciation period. Other factors may enter, all of which indicate that the determination of the proper depreciation period is largely a local one.

In an operating plant, the depreciation rate may be suddenly altered due to a material improvement in economy by the addition of other equipment to the existing plant. For example, the non-condensing reciprocating engine (and in many cases the condensing steam engine) has, during the past few years, had its economical life extended by the advent of the low pressure turbine, the combination of the reciprocating engine and the low pressure turbine giving a materially improved overall economy at a comparatively small added investment charge. Low pressure turbines are, in the majority of cases, installed in reciprocating engine power stations so that land and building charges are distributed over a materially increased installation. This same consideration may, in the future, be applied to the depreciation period of a gas engine plant in which, by the installation of low pressure steam turbines operating from boilers which utilize gas engine cooling water and the gas engine exhaust as sources of heat. The writer believes that subsequent events will show this item of depreciation to be in error more frequently than any of the other estimated charges, either fixed or operating and it therefore behooves commercial engineers to give the matter the most comprehensive investigation.

Mr. Parker, in treating of the subject of "supervision" states in effect that the plant should be charged with uneconomical supervision. The usual manager, particularly the manager of an industrial plant, may not have sufficient knowledge to properly handle or supervise the power plant installation. Because of such a limited knowledge, more of his time is required than if especially trained supervision were employed. This specially trained supervision could, in most cases, be obtained at a lower rate than the rate being paid the manager and therefor the supervision charge would be materially decreased. It appears unfair therefore to charge the plant with more than the cost of proper economical supervision other than that of the local manager. The effect of this special supervision will also be to reduce the total investment because of the superior knowledge of the trained supervisor leading to economies of which the local manager would be ignorant. If proper supervision is not employed, then it appears to the writer that an additional item of fixed charge should be incorporated entitled "bad management" as an exhibit for future comparison.

C. A. Graves: The writer would like to emphasize the point brought out by Mr. Hibner regarding the selection of a competent engineer to advise in regard to the power plant installation.

This engineer should not only be familiar with power plant equipment, but also competent to advise in regard to the layout of the machinery, shafting and motors. The industrial manager is interested, primarily, in the power cost of the manufactured product rather than the cost per kw-hr. and, while a power plant may be installed to produce a certain number of kw-hr. at a rate of, say 3 cents, if the proper care had been exercised in installing the motor equipment, a smaller amount of power would have turned out the same amount of manufactured product at a lower cost though the cost per kw-hr., may have been increased to 3½ cents.

Power, whether purchased or generated, should not be wasted, and to prevent waste, attention should be given to the laying out of group or individual motor drive in such a way as to balance the shafting friction against the motor friction or efficiency. Many installations are over motored, and it is also a common error to take the sum of the average motor loads as the average load at the switchboard. The switchboard load, however, is less than this sum, the difference depending on the number of motors and the class of the work; and switchboard watt-hr. meters will register considerably less current than is usually estimated.

Another common mistake is to give as the maximum demand, the sum of the estimated demand for power and the demand for lights, forgetting that the peak load for power in most industries comes about 10 or 11 a.m. and that the load is below the average at the time the lights are turned on around five p.m. These abnormal estimates as to the maximum demand and kw-hr. consumption are favorable to a private plant in most cases.

Now, if in taking up a new proposition the layout of the shafting and motors are considered first, and the question of the purchase or manufacture of power taken up after the machinery has been laid out in the best possible manner, it will be found that central station service in the majority of cases will be best suited for the case. Another point which should be considered is the fact that the price of coal is tending to increase, or the grade to decrease. This means that the cost of power will tend to increase in a private plant. On the other hand, the tendency of central station rates is to lower, because the station load factors are improving; the increased cost of coal having but little effect on the central station's cost of delivering power, because it is so small a part of their total cost of serving their customers; so that within a few years proposed private plants will be generating current at costs higher than it can be purchased. This brings us back again to the amount to allow for obsolescence: and the question should be "How many years will it take before the central station price reaches the cost of generating in the private plant."

It seems to the writer that the central station men think that the consulting engineer will always advise an isolated plant because some plants operate cheaper than the quoted rates, and the consulting engineer believes the central station man wants to get every private plant shut down because some plants operate cheaper on street service.

At the rates quoted by central stations there is a portion of the private plants in their locality which can operate as well or better on the central station service; there is a portion of them which operate at a little lower rate than that quoted; and there is a portion which operate at a considerably lower rate than quoted.

Central stations, as their business grows and the diversity factor increases, are making rates which will secure to them the most profitable business, and many loads which are good for private plants are better for central stations, so that a certain portion of these private plants will be shut down at each reduction of the central station's rate.

Frank F. Fowle: Mr. Parker's paper presents some of the phases of a very live question which is present in nearly every locality where central stations are campaigning vigorously for new business. The issue is the central station versus the isolated plant—not a new problem, but one that promises to remain with us indefinitely and one which constantly reveals new angles.

The owner, or prospective owner, of an isolated plant is the person who most deserves sympathy, for he is beset on one side by the central station man and on the other by the manufacturer of isolated plant equipment, each of whom is determined to have his business, at almost any cost. In the midst of this keen and sometimes bitter competition, it is not to be wondered at that the owner is perplexed over the extravagant and conflicting statements often set forth by each side. This is clearly a situation wherein the disinterested consulting engineer can be of the greatest service to the owner. In many cases the owner avails himself of such service; and again he decides the issue himself, often to his ultimate loss.

The central stations and the manufacturers, recognizing the owners' need of engineering advice, are now generally equipped with sales engineers, or men in an equivalent capacity, whose services are tendered without direct charge. Without denying the expediency of such a plan from the sales standpoint, it is important for the owner to see that such advice comes from partisan sources and he ultimately pays for it, although perhaps not realizing that fact.

Both sides sometimes represent to the owner that he needs no consulting engineer, because their engineers are equally qualified to advise him, with the benefit (apparently) of no expense on his part. Frequently the owner accepts this proposition and relies entirely upon such advice. For his own protection, however, in such a case, he should have the plans and estimates thus prepared submitted to a disinterested engineer for the purpose of checking them and passing on the question of economical operation.

The position of the sales engineer is clearly partisan, for he cannot justify himself to his employer unless he secures business which would not otherwise be secured—and his work thus partakes of a commercial character in a large degree. It is also considered legitimate commercial tactics to so plan the owner's installation, whatever it may be, that he will find it inadvisable or perhaps very difficult to change his policy after it is once adopted.

This implies no fault-finding with existing practices, because every business man is presumed to have sufficient business acumen to protect his own interest, either personally or through those whom he retains. At the same time it is quite proper to point out the results which often attend such practices where the owner is unqualified to pass on the issues and fails to avail himself of advice which is neutral with respect to the competing interests. The owner is the one who must assume the risks and bear the losses, if any there are.

A study of Mr. Parker's paper brings out clearly the importance of considering and weighing carefully every item of cost, under each operating assumption. The matter of depreciation is of course vital, and should no more be over-estimated than under-estimated. The use of the term amortization in the sense of physical depreciation conflicts with usage which has hitherto obtained. The term depreciation implies the shrinkage in value of all physical property, while amortization covers intangible capital, such as franchise cost, organization cost, licenses with a fixed term, etc. In the present case, under the definition just given, amortization would play practically no part.

The method of securing a depreciation fund which Mr. Parker discusses, by the accumulation of a sinking fund from semi-annual increments at compound interest, is not universally accepted as a satisfactory theory of depreciation. An account of some discussion on this subject by the writer will be found on page 796 of the October 6, 1910 issue of the *Electrical World*. The issue here is between the sinking-fund curve and the straight-line theories of depreciation. The difference is not consequential in relation to the average annual assessments to create the reserve fund, but concerns the present value of the plant at any intermediate stage of its life. There is a marked difference between the methods in the last respect, with numerous arguments in favor of the straight-line theory. The latter is considerably the more conservative of the two and it accords most nearly, in the writer's opinion, with the encroachments of true physical depreciation and the corresponding shrinkage of serviceable value. The straight-line method assumes compound interest on the accumulated fund, just as in the other method.

The marginal theory of investment return is important to consider, of course, but Mr. Parker's deductions from it can perhaps be carried further. In general it may be said that the whole investment in an industrial enterprise consists of plant or property, raw material and stock on hand, product in the course of manufacture, finished material and stock on hand, furniture, fixtures, tools, teams, etc., and liquid assets or working capital. The power plant, as a profitable investment, is no different from other property which can be rented. For example, if the average profit from the business is quite high, and an equivalent interest rate be applied in computing the cost of owning, say, a warehouse, it is almost a foregone conclusion that it will be cheaper to rent than to own one. And so on, any property or plant which can be rented will generally be cheaper than ownership under a very high rate for the use of capital—that is, the capital can be used more profitably in the enlargement of the output capacity or the sales organization.

On the other hand, if the rate of return is low comparatively, the ownership of much property and plant may be an economy and the lower the rate, down to the usual return on safe investments, the more plant it will pay to own. But, in the first case the concern's credit will be much better than in the second, under like management, and the needed capital would be attracted, whereas in the last case the capital might be difficult to get—which shows the anomalous results of the marginal theory as thus applied.

Mr. Parker's discussion of the curve in Fig. 1 of his paper is extremely interesting, and the conclusions drawn from that particular curve seem to be sound. But it is quite obvious that the curve may take some other form and thus modify or alter the conclusions. It is also noteworthy that the growth and expansion of an industry is not alone a matter of capital; it is also dependent upon capable management and salesmanship and again upon the existence or creation of a market, with possible competition. Any business or industry which earns 20 per cent net for a long series of years, through successive periods of prosperity and depression, is remarkable and indeed the exception. It is reasonable to suppose that such a business is a protected monopoly or one enjoying quite exceptional advantages. Ultimate competition may conservatively be expected and such a result tends always to depress prices and reduce the profit.

The prime requirements of a growing business may not be so much a matter of capital as one of aggressive salesmanship; and if the net returns are large, it is obvious that the new capital thus created can be returned in part to the business, if needed. The concern which owns a well constructed plant, equipped for economical operation, is the one in the strongest position to weather a period of depression or resist competition. Low production costs admittedly may not be imperative when business is at its height and profits are large; but the inability to attain low costs may be disastrous when conditions change.

It seems to the writer that it is more conservative to assume money at 6 per cent, or even 7 per cent, and compare the economies on this basis, leaving it to the owner to decide where his capital can be used most advantageously. The owner is the final arbiter, in any case; while the function of the engineer is to set the real facts clearly before him. A decision not to install an isolated plant when, for example, the investment will earn 10 per cent, while the industry in question earns 15 per cent, is not fundamentally a question of the comparative economy of the central station service versus the isolated plant, but one which concerns the supply of and demand for capital, and the price at which it can be had, in view of the risks involved.

One more feature of Mr. Parker's results is worth careful study. The results of Table III show quite a saving in favor of central station service. On the isolated plant side there are several items which are perhaps open to discussion. The assumption under emergency service that there will be four days shut-down per month seems excessive; in fact the need of emergency service is open to question, and Mr. Hibner, in the comparison in his paper, assumes none. When the plant units are subdivided there ought to be a very small chance of full shutdown. The allowance of $1,000 for manager's time seems like rather expensive supervision, and it may be noted that no such expense is carried in the other account, which seems hardly fair. Clerical expense at fifty cents per hour is also a rather high item. The rental value of the floor space, at one dollar per foot, may be proper of course, but it is high for many industrial plants. Revising the table and taking fixed charges at 12 per cent, equal to 6 per cent interest, 3 per cent taxes and insurance and 3 per cent depreciation, which are fully ample, it would appear about as follows:

	Central station	Isolated plant
Fuel	$1380	$2290
Ash removal	16	25
Labor	1080	2780
Supplies and repairs	160	366
Water	12	60
Electric service	6250	
Elevator service	415	415
Fixed charges, 12 per cent	384	2304
Supervision	200	500
Clerical expense	25	150
Rental of space		500
	$9931	$9390
Saving		541

This result is in considerable contrast with $2,816 on the opposite side of the balance sheet. The showing in favor of the isolated plant is not marked, but it would probably increase with the growth of the industry and the size of the plant. The owner's decision is not necessarily in favor of the isolated plant, for reasons before given; but a statement in such form is at least conservative and it leaves with the owner the question of deciding where to use his capital or his credit to the best advantage.

In addition to my remarks on Mr. Parker's paper, in relation to the interest rate to be used in computing fixed charges, which apply also to Mr. Hibner's paper, there are a few points of further interest.

He emphasizes clearly the influence of the uses for exhaust steam, which is often the factor that really controls this question. In fact, when the industry uses steam in considerable quantities in manufacturing processes, in addition perhaps to heating, it is very difficult if not impossible to show superior economy for central station service. Power in that case is essentially a very cheap by-product. When there is little or no such use for steam, on the opposite hand, central station service is ordinarily the cheapest by a considerable margin.

In some cases another feature presents itself which has an important bearing on the net economy. This is the possibility of selling exhaust steam or electric energy from an isolated plant to neighboring industries or business concerns, or perhaps to tenants on the same premises. The revenue thus derived must be in excess of the bare operating cost for the service rendered, of course, or it will represent a loss; but it will usually show some profit and diminish the fixed charges. This plan will be most profitable where some diversity in the different demands is present and where the retailed steam or power is not of sufficient quantity to necessitate a very material increase in the size of the isolated plant. The latter cannot ordinarily compete with wholesale rates for electric energy unless the exhaust steam is needed in industrial processes or can be sold; neither can it afford to distribute either steam or power to any great distance. But in a compact district the sale of by-products may show considerable profit.

In comparing tables I and II of the paper it is notable that 5 per cent profit is included in the fixed charge in the second case, but not in the first. As pointed out in connection with Mr. Parker's paper, there is no reason why the power plant, as an investment, should be put in a class by itself and assessed with an interest rate equal to the average net profit on the whole industry. The same rule should be applied in table I to the heating plant, but preferably not to either plant. Applying it to both plants, it is obvious that the higher the interest rate the greater the disadvantage under which the power plant is placed, because it represents a much larger investment than the heating plant.

Taking away in Table I the 5 per cent profit, amounting to $575, leaves the net additional cost of power over heating as $4926 or $0.0205 per kw-hr. This compares very favorably indeed with wholesale rates for electric energy. The central station rate given in table III of Mr. Parker's paper, with slightly larger demand and consumption, is $0.0247 per kw-hr.

Taking away the 5 per cent profit reduces the unit cost about 10 per cent.

Similarly, taking away the profit in table III, amounting to $845, reduces the unit cost to $0.0217 per kw-hr., or about 13 per cent. This does not affect the question of comparative economy, however, between steam and producer gas, except in a small amount.

Looking at this whole question in a very broad way, it appears from the standpoint adopted here in the case of the isolated plant that the more profitable the industry the less the economy of production need be considered. On the face of things this may seem true, but in terms of gross costs and volume of net returns it is not true. Prosperity begets extravagance and from a state of great prosperity many propositions can be deduced theoretically which are largely artificial. For the ultimate gain of the community the central station ought to acquire all business which conservative economy justifies it in having; at the same time the acquisition of business which can be handled most economically by an isolated plant, is an economic burden in the end.

H. G. Gille, Thomas M. Gibbes: We have gone over Mr. Parker's paper somewhat in detail and feel that he has covered the subject very thoroughly. There are, however, a few points that cannot be emphasized too strongly.

Our experience is that industrial plant owners rarely if ever consider anything in the form of investment except the engine and generator. We therefore feel that the items enumerated by Mr. Parker should act as a guide for working up the investment of any industrial plant.

The item of insurance is a matter of great importance both in industries where inflammable material forms the part of the industry and also where a life hazard is contracted, such as in department stores and public buildings.

Interest on investment, depreciation and obsolescence are thoroughly covered and need no comment.

Supervision and fair profit are probably two items that are rarely if ever considered in the cost of producing power. A parallel case would be the machine shop, they would not consider for a moment installing a milling machine or a gear cutting machine if the amount of money saved on the product of these machines amounted to only a fair interest on the investment of machinery, as no business could exist if a profit was not earned on top of such interest.

R. Norsa: There is one point in Mr. Parker's paper that I will briefly discuss; that is the straight line formula which has been assumed to represent the *investment* cost in a plant. The author has pointed out that the linear equation $\$ = A + B \times \text{h.p.}$ is only roughly true. But, as a matter of fact, we start out with this approximate representation of the investment cost, in order to come to a practical application on the sale of electrical energy;

therefore it seems very important to investigate if the above expression is sufficiently rigorous.

Now this question of cost seems to me much more complex than can be represented analytically by a first degree equation, or graphically by the corresponding straight line. Of course no law of cost is susceptible of reduction to a mathematical form. Only in a few cases some theoretical investigations are possible, as *e.g.*, for the prices of some machinery.

Thus for a line of transformers of a given design and type, it may be shown that the weight of active material increases approximately as a certain power n of the rated capacity, and it may be assumed to vary according to the equation

$$\text{weight} = \text{constant} \times (\text{kv.-a.})^{n}$$

This would be a linear relation if $n=1$. But if in all transformers of the above line, induction and current density are the same, that is if the losses per unit weight are constant, then n is approximately equal to $\frac{3}{4}$. Consequently the law is not linear but parabolic. As regards the cost, the law will not be very different, and therefore we see that with the increase of capacity, there is a decided saving in weight and consequently a gain in cost. This well known example has been recalled only for the purpose of showing that, even in theory, the straight line formula does not generally hold.

If now we consider the investment in a plant as a whole, the law of the cost becomes very complicated; this law will generally not even be uniform and is not mathematically determinable. We may however admit that a mathematical expression may have some value if it approaches the average conditions, and we may agree that for a plant of a given capacity the *actual* cost may fairly be represented by a fixed expense A and a cost B for each kilowatt. But if we assume A and B as constants and we write

$$\$ = A + B \times \text{kw}.$$

then this equation is supposed to represent the *law of investment cost* in the above plant and consequently it may be applied also to an additional investment, or in other words we assume for each added kilowatt the same cost per unit B, as given by the analysis of the present plant. Now if it is not easy to predict generally what investment will be required by each added kilowatt, we may however state that the cost of the added capacity will very likely be different from the present. If the addition does not require some substantial modification, the added capacity will generally correspond to a lower cost B per unit. Practically we may attempt to follow roughly the law of cost, by saying that the investment is made up of B_1 dollars for each of the first K_1 kilowatts, *plus* B_2 dollars for each of the next K_2

kilowatts and so forth, being $B_1 > B_2 > B_3$ . . . . etc. That is, the coefficient B is no more a constant but varies according to a sliding scale depending on the capacity.

We have above been discussing the cost as regards the investment per kilowatt of central station capacity. Now when we come to examine the sale of energy, one of the elements on which we must fix our attention is (as Mr. Parker already pointed out) the value of the service as determined by the cost of securing an equivalent service in some other way, for example by a private plant. As regards the investment costs of isolated plants, we may now repeat exactly the same considerations, and consequently we shall see again that a straight line formula is not suitable to express the investment costs of these plants; but we shall find as before that the cost B per kilowatt decreases with the increase of the capacity.

On the other hand it is also well known, that with increasing demand of a consumers plant, the cost to the central station of having the service ready at his premises generally increases *with decreasing rapidity.*

The foregoing remarks have been confined to the investment cost and the conclusion may be expressed very briefly. Mr. Parker has very clearly shown the opportunity of a gradation of the B charges on account of the seasonal diversity depending on the seasonal demand of different consumers and also on account of the daily diversity depending on the daily demand at the time of the peak. But as the coefficient B is not a constant, a still further gradation of the B charges, according to greater or smaller demands, should also be considered.

DISCUSSION AT BOSTON, MARCH 22, 1911

Henry D. Jackson: I have read Mr. Parker's paper with a good deal of interest, and in this connection one point strikes me particularly, and that is that if the fixed charges are to be handled by the sales agent of the central station as indicated in this paper, there seems no good reason why the fixed charges on the central station should not be handled in a corresponding way. Certainly the central station has to figure on the profit ratio if the industrial plant has to; and further the amortization rate in a central station is higher than in most industrial plants, for the machines are usually far harder worked and also are scrapped much earlier in their life. These points taken into consideration, there seems no reason to believe that the fixed charges against a central station should be much if any less than against an industrial plant. I have figured that the

Marginal interest would be	5	per cent
Amortization practically	5	per cent
Taxes and insurance	2	per cent
Fair profit ratio	11	per cent
Making a total of	23	per cent

On this as a basis I have made an examination into the reports of one or two of the lighting companies and taking their own figures as regards the cost of the plant, including real estate, one-half of which has been charged against the plant—steam plant, electric plant, electric lines including transformers, meters and arc lamps, and have charged 23 per cent against these. I have taken the operating expenses including station, distribution and management. I have taken the income as given in this report, which undoubtedly includes not only the income from the sale of current, but other sources of income. I have also taken into account the total kilowatt hours generated as given in the report, and the total kilowatt hours sold. From these figures we discover that this Company has received for total kilowatt hours generated, remuneration at the rate of 4.7 cents per kw-hr. They have received per kw-hr. sold, 6.6 cents.

Their expenses have been:

Operating, including distribution and management per kw-hr. generated	2.5	cents
Per kw-hr. sold	3.5	cents
On their fixed charges, the cost of kw-hr. generated is	4.7	cents
Per kw-hr. sold	6.5	cents
Making the total cost of their power per kw-hr. generated	7.3	cents
Per kw-hr. sold	10.0	cents

Evidently then, the central station or this particular central station is operating as a philanthropic enterprise, furnishing power purely for the love of it, because it is quite evident from these figures they are operating at a loss. Nevertheless the stock of this central station stands at a very high figure in the market, and the company is paying large dividends. Evidently they do not use the same basis of figuring as Mr. Parker would have the sales agent of the company use when figuring the cost of power for any industrial enterprise.

I would like to ask, therefore, the central station argument for charging by one method against the central station, and by another method against the industrial plant.

Mr. Kelley: Mr. Hibner states, in regard to power used, "Nearly all of them will tell you that their load is absolutely constant." Another point that they will tell you, if you are seeking to obtain data for a power estimate of their requirements, is that their machinery runs very steadily. I recall one instance where it was necessary to estimate as closely as possible on the probable requirements of the customer in order to conclude a contract. From my own data I took the power required for the machinery, and I went to the proprietor for information as to the time the different classes of machinery had been in operation. Taking that data and working it out I found my power cost was very much higher than I knew it should be in that plant, and by putting a man in that plant with a stop watch on each class of machinery for two days I found that in some instances the time he had given was actually four times the actual time that machinery was in operation. To give you the conclusion of that affair, the contract was made by the central station with the party on these terms: that the estimated power consumption, if he allowed the central station to place his motors and to make the installation themselves, would be about $50 a month. The central station would put in the plant at its own expense, let him run it a year, paying the bills rendered, and if he was not satisfied at the end of the year would take out the plant at no expense to him except for the power taken. I recollect that the average of the first six months was $47.75 that was paid for the plant at that time. It illustrates the accuracy with which the cost of operating an industrial plant can be predetermined if the factors are all given proper value.

In regard to the statement given in the paper, the difference in cost, or reduction of cost, by a differing use of steam in a steam plant. I can give you the results of power cost estimates that have recently come under my observation. In one case it was that of a plant operating about 1,000 lights and 55 h.p. in motors. The plant used current both for light and power, and mechanical use of steam, for the 24 hr., of course in varying quantities.

The plant consisted of one 125-h.p. engine, 275 rev. per min., direct coupled to a 75-kw. generator, and a 40-h.p. engine direct coupled to a 25-kw. generator. The total of costs for the year, including all the items that have been included in these estimates previously given, was 2.022 cents per kw-hr. That is rather a surprising cost, and it is simply due to the 24-hr. operation and the large use of steam, which reduced the power cost materially over what it would have been if this mechanical use of steam had not existed. That illustrates the fact that almost every industrial plant must be valuated on its own basis; you can't use averages.

For another plant the data is roughly as follows: the total power required was about 1,000 h.p. The water power available varied from 200 h.p. to 400 h.p. and the difference in the amount of industrial power demanded during different seasons of the year ranged as high as 200 h.p., this making a possible maximum variation of about 400 h.p. These conditions were looked into by a central station that desired to provide power. The proposed installation called for a maximum of 500 kw., with an average yearly power of 380 kw., and the price named was something under $30 per h.p., without stating where the power was to be measured. The cost of that plant as it was operating at the time the data was taken was about $27.50 per i.h.p. With a plant laid out aggregating about 790-h.p. in motors, there being 91 in number, and the steam plant re-organized on the basis of the most economical operation, the cost figured out 1.485 cents per kw-hr. The items covered in that estimate are coal, labor, miscellaneous, supplies, oil, removal of ashes, repairs, interest, the amortization, insurance—both regular boiler insurance and liability insurance—taxes, charges on three months supply of coal, and the charge for supervision.

Another plant had some 500 h.p.—I think exactly 523 h.p.—in motors installed. The company was buying power. It was at the same time operating 500-h.p. in boilers, and supposed it was using steam economically for mechanical purposes for an engine of 75-h.p. and various pumps. Their annual bill for light and power was something over $13,000. By a proper installation on its own premises it reduced the cost of power from 2½ cents per kw-hr. to one cent a kw-hr.

So you can see that every plant must be valuated, upon its own conditions, and all conditions must be taken into account.

John West: The question upon which Mr. Hibner has based his paper, " The Cost of Industrial Power " is " Shall I purchase my power from a power company, or are my conditions such that I can produce it cheaper myself." Mr. Hibner has answered this question by a very accurate estimate of the additional cost for power in the operation of the proposed steam plant. I think, however, that those industrial power engineers who are employed by central stations will agree that the marginal difference between the cost for central station electric power and the cost of manufacturing power in a private plant is in many instances very slight. The facts that live steam for industrial heating, large demands for factory lighting, and the use of factory residue for fuel, enter largely into many industrial power propositions make such conditions typical of the average problem; and to what extent these items will affect the cost of producing power is dependent entirely upon many conditions, as Mr. Hibner has pointed out. This does not mean, however, that the central station industrial power engineer is justified in abandoning his efforts to obtain power business when such conditions are encountered and the engineering data obtained proves discouraging.

It has been proven beyond a doubt that through the use of central station electric power service, certain economies are effected the value of which should be taken into consideration and used to offset the conditions which would seem to prohibit the use of central station power.

While we are considering the manufacturers' lack of technical knowledge and his inability to determine the cost of industrial power it should be remembered that the majority of manufacturers look at the cost of power from the standpoint of its relation to the total cost of production, and for the sake of convenience usually combine light, power and heat to one account. Their figures may be in error from an engineering standpoint, but the fact remains that if a manufacturer considers that his plant investment has paid for itself, and if his credit standing is such that funds are available to the amount necessary to replace his equipment, it is likely to require conclusive proof of the benefits which he will derive from central station power service in order to obtain his business. Therefore, it is my personal opinion that industrial power engineers engaged in central station work should regard the cost of power from as near the manufacturer's point of view as it is possible to do, and base their arguments upon the economy which central station power represents.

The highest possible price for central station power service should be the result of industrial power engineering; and the true cost of power would seem to be a relative factor in which the value of the service should be considered.

In order to show the value of central station service it is sometimes necessary to make comparisons of economy between manufacturers who are competing in local markets, and the value of such comparisons is of course confined to local application. I have in mind the operation of two manufacturing concerns. Their methods of operation are almost identical and each believes that his operation has approached its highest efficiency. One of these manufacturers has a steam power plant located in the basement of his factory from which steam for heating and manufacturing purposes is supplied and power transmitted to the machinery by mechanical drive. Factory lighting is supplied from a generator which is driven from the engine. The rate capacity of this plant would be 150 kw., and it is being operated at very near full capacity. The other manufacturer employs central station service for power and lighting and maintains a heating plant for factory and industrial heating. A large part of the exhaust steam in the private plant is used for heating, factory residue represents a large portion of the fuel, and the cost of industrial power and light is reduced to a very low figure. In contrast with this figure the rate which the electric company received from the other manufacturer for power and light is high.

Such a comparison would seem to indicate that the private steam plant is the better proposition. By a careful investigation of the gross yearly valuation of the product of each factory and an adjustment of the quality of the products to the cost for power, heat and light it may be shown that the total cost of these three items would represent approximately one-half of 1 per cent of the gross valuation of the product in either case. This bears out the assumption that the cost for industrial power whether obtained from a central station or manufactured in a private power plant will result in approximately the same economy for similar conditions of operation. In this particular instance it becomes necessary to employ some such method of presenting the cost equalizing advantages to be derived from central station service in order to prevent the loss of the business of this central station customer and his neighbors and to forestall the installation of a suggested private steam electric plant to supply light, heat and power for the several manufacturing plants that come in the legal limits.

In reducing the cost of power to an economy basis the chances for error are of course increased, but from a commercial standpoint my experience leads me to believe that the human element enters at this point, and its attitude which has resulted, according to Mr. Hibner's explanation, from ignorance of technical detail, and the desire to reduce the cost of production may be turned to the advantage of the central station power service without misrepresentation of facts.

Mr. Lundgaard has stated in his discussion that Mr. Hibner's paper has been very clear in defining the various factors and really does not leave much to be said when the discussion is limited only to cost. I quite agree with him in that Mr. Hibner has accurately qualified his assumption.

I think however that while, with reference to geographical location, the example he has chosen may be "a typical example of the conditions ordinarily found," it rather serves to exemplify an excellent opportunity for the installation of central station service, than to typify the general average industrial power problem. A commercial load factor of 80 per cent is not unusual for 10-hr. operation in shoe factories but is not generally found when a period of 3000-hr. is considered. The relation of power cost to power value is unnecessary from the central station viewpoint in this example, but if we admit that central station power service would result in an increased production over the use of similar service from a private steam electric plant we are able to arrive at some interesting results. I have assumed that the increased production in this case would amount to 1 per cent for an equal amount of energy consumed. If the gross yearly valuation of the product of the Toronto shoe factory would amount to $1,000,000 and the net profits 25 per cent then this 1 per cent increase in production amounts to $2,500 which has the effect of reducing the cost of power 45.4 per cent. It is not unreasonable to suppose that such advantages as the use of the elevators during the noon hour and for overtime work to facilitate shipment of product and the convenient handling of materials, and the security afforded against shut-downs which will enable the safe working capacity to be increased, together with the continuous coöperation of central station engineers in effecting the highest efficiency of application would result in this increase of production.

If we disregard those advantages which are distinctively inherent to central station power service and which may be said to result in a better quality of power than it is possible to obtain from any other source, we are sure to weaken the position of central station power. We would not seem to be doing full justice to the subject of the cost of industrial power if we excluded the value of quality; and without a standard of economy upon which to base our comparisons of costs I feel safe in the assertion that much power business will be lost to central stations.

C. A. Adams: These papers are very interesting from several points of view. They are encouraging in that they are frank and earnest efforts to reduce to a more rational and scientific basis the computation of the real cost of power; but, when coupled with the discussion, they are very discouraging in that the opinions expressed by various speakers of broad experience and high standing in the profession differ so astoundingly on the vital point at issue, and almost always in the direction of the economic interests of the speaker; in other words it is an illustration of the old theory of economic determinism. It would seem that of all men, engineers from their experience in close contact with the unchangeable laws of nature should be able to see such problems apart from their commercial interest.

Referring now more specifically to the papers, Mr. Hibner appears to have neglected one consideration which may be of considerable import. When considering the cost of power it is very important to know how much of the exhaust steam is used for heating or for industrial purposes and how much of it is wasted; but to this end it is not sufficient to know the relative monthly or daily demand of steam for power and other purposes, since it is quite possible that where the demand for industrial steam during the regular working day considerably exceeds the demand for power steam during the same period, some of the exhaust steam may, nevertheless, be wasted owing to the lack of coincidence of the peaks of the demand curves for industrial and power steam. I know of plants where this is actually the case and where it means an appreciable increase in the real cost of power.

Turn now to the question of profit and the marginal principle referred to in Mr. Parker's paper. The principle involved and its application to the commutation of the cost of power is unassailable, but the opinion as to a fair profit (11 per cent) over and above the 6 per cent interest is one with which I cannot agree. The assumption that the average promotor or investor is not attracted by less than 17 per cent return on his investment is somewhat astounding to those who consider themselves mighty lucky to get 6 per cent. If central stations earn 17 per cent, which I do not believe, it is no wonder that we have so much agitation for public ownership.

Moreover if the promotor or owner of a plant stops his investment when the marginal investment ceases to earn 17 per cent, it is to be assumed that he can place any additional capital he may have at that figure. Why then should not the amount set aside for amortization be earning 17 per cent rather than 6 per cent which is considered too high by many.

Since the profit ratio is a quantity concerning which there is a wide difference of opinion, and since the 6 per cent interest is fairly well agreed upon, would it not be better to exclude the profit from the fixed charges in figuring cost of power. This would reduce power-cost to a parity with the cost of other things,—what we have to pay for them. Then the profit in the manufacture of power could be figured for each case, and if it fell below the desired point, the proposition would be discarded as not yielding enough profit. The result is obviously the same, but the method here proposed would eliminate a large amount of unnecessary and profitless discussion.

I have here some figures on the cost of power in a particular plant which may be of interest. It is the case of an industrial establishment where the total amount of steam consumed is vastly in excess of the amount required for power, and where all the exhaust steam is utilized. Including even the 17 per cent (6 per cent interest and 11 per cent profit) fixed charge in addition to insurance, taxes and amortization, the total cost of power per kilowatt hour is only 9/10 of a cent; and without the profit, simply charging 6 per cent interest on the money, the actual cost of power comes to about 56/100 of a cent a kilowatt hour. These are not figures concerning which there is any doubt, everything has been allowed for. The reason for the low cost is that the plant runs 144 hours per week at a load factor of at least 80 per cent and all of the exhaust steam is used for industrial purposes.

N. T. Wilcox: What is the price of coal?

C. A. Adams: The price of coal is $2.20 and the plant is on tide water.

J. F. Vaughan: Referring to Mr. Adams' discussion of fixed charges, it is common in new enterprises to divide the interest item into two parts; one, straight interest for raising the money, and the other a certain percentage for covering the risk of investment. It would seem reasonable in comparing a central station with some isolated plant to allow the same percentage for covering the "reasonable risk" in each case. In a going system, however, allowance for such risk is not justified except in cases of considerable extension or a development of new business.

There is one point that I should like to refer to in Mr. Dudley's discussion at Toronto, of Mr. Hibner's paper, and that is the ambiguity of the term "horse power year" as ordinarily used. He brings out clearly that this term means nothing unless the load factor is stated. He gives some interesting data on this question of load factor in manufacturing plants of various kinds; for instance, the load factor for cement mills is given as 85 per cent, textile mills, cotton mills, etc., 75 per cent to 90 per cent, and so on.

C. A. Adams: They are 10-hr. load factors, are they not?

J. F. Vaughan: They appear to be 10-hr. load factors.

Mr. Cook: I would say that one of the points to be considered is whether it is 10-h.p. or 10,000 h.p. and these figures that Professor Adams presented don't mean very much to me unless we know how large the plant is.

C. A. Adams: 1000 h.p.

Thomas M. Roberts: I should like to put one of the first sentences of Mr. Parker's paper with one of the final sentences of Mr. Hibner's. Mr. Parker speaks in regard to the fixed costs being determined somewhat by the *first layout*, and Mr. Hibner's paper in the final sentence in regard to the time in the future when no factory will be without its *consulting engineer*. I have just recently had occasion to visit one of the large mills of New England, and the agent for the mill being one of the shrewdest business men, probably, in New England, and he sees immediately where advantage is gained by putting capital into the right investment to improve his electrical equipment for his mills. When it is pointed out that although an underground system will cost more than twice as much as a pole line system to distribute the power of the mills he immediately sees the advantage of that underground system, in that the cables can be put closer together, less copper is involved in carrying the power some 1,000 or 1,500 ft., and the maintenance of the underground system when once installed is very small, in fact it is there to eternity, relatively speaking, by the side of other apparatus; and he sees in figuring up his coal bill that in the course of a year on something like $60,000 worth of coal he can gain ¾ of 1 per cent, say, on the investment, by putting things underground instead of overhead. Well, that is a margin, and it is worth financiers' notice.

The cost of copper now is low; we don't know what is liable to happen. It is liable to go back to where it was a few years ago, up to 20 cents a pound. And yet the first cost of apparatus in transmission is a very decided factor in the problem here, although this paper does not discuss that end of it. It seems to me that the first installation, properly installed, means a very marked factor in the fixed costs on the coal bill. I have come across many cases where a plant is already installed and a manager wants to supplement it with new motors, he will say, "Here, we have running through the mill so many circular mils of copper and it is not half loaded yet according to the insurance rules." Well, when we come to figure out the amount of copper he has, and the voltage drop, if it is alternating current (the reactance factor running perhaps nearly three times as much as the resistance factor), we find unless he adds considerably more copper he will not get the right voltage delivered to the motors. That brings up the question of voltage, or the main factor in transmission. A large portion of the mills throughout New England are based on 600 volts at the switchboard and 550 at the motors, yet there are quite a number that are not afraid of 2300. It means not only fulfilling insurance rules, but it means a decidedly less first cost on the copper; it means a decidedly less $I^2 R$ loss, which is continually eating up the coal bill; and the time may come, (and I feel quite confident personally that it will come), when 6,600 will be delivered into the mills instead of 600 or 2300. It is simply a matter of educating the general engineering public, and especially the fire insurance people, to the fact that it is no more dangerous, so far as the risk is concerned, when properly installed, than the lower voltages.

It seems to me, as engineers, we cannot dodge this question of getting the power from the centre to the consumers, or to the receiving units at low cost; and that it is poor economy for a consulting engineer in laying out a plant to put the power house down by the water unless he can balance up against it the additional cost of transmitting the energy to the center. Let me put that another way. Let us suppose that the central power station, at the mills, is near the water, and it is also at one end of the mills. Now, the consulting engineer must balance up the advantage of being near the water for condensing purposes and delivery of coal, against the added cost of transmitting the energy, say several hundred or a thousand feet, as the case may be, to the farthest mills; while if he puts the plant in the center of distribution and carries his coal a little farther, and first puts up the price of an extra circulating pump, or something of that sort, in his auxiliaries, he may find—and certainly putting the costs side by side he will find—that it is better in the end to put his power station in the center of distribution rather than down by the water to save the cost of a circulating pump. To me these factors are coming up continually in meeting the extension equipments and new equipments in New England mills, and it seems to me are overlooked very largely by the manufacturers themselves.

F. M. Gunby: The cost of power has been discussed to quite an extent, both as to the gross and net costs. But the cases sighted, in which part of the by-products of the steam plant were used for heating and manufacturing, were confined mostly to plants in which heating only was required.

I wish to say something about the credits to the cost of power in plants where more of the by-products of the steam plant are made use of. The net cost of power to a manufacturing concern is the gross cost of power minus the costs of all of the waste products which are made use of in the manufacturing process.

These remarks refer principally to plants of fair sizes, such as might be found in textile mills. By fair sizes, we mean 500 or 1000 kw. and upwards. I will refer below to " bleeding " steam, by which I mean steam which is taken from between the cylinders of a compound engine or from between the stages, or parts corresponding to stages, in turbines.

Mr. Charles T. Main stated in his paper entitled " Choice of Power for Textile Mills," read before the National Association of Cotton Manufacturers in 1910, that the gross cost of power might be reduced by the amounts given in the table below by the use of steam bled in the manner described. This table was made up originally to apply to steam engines, but is also practically applicable to turbines with slight modifications:

Per cent of steam used (bled)	Coal at $5 per long ton per kilowatt year	Coal at $4 per long ton per kilowatt year
25	$3.00 to $4.00	$2.40 to $3.20
50	6.00 " 8.00	4.80 " 6.40
75	9.50 " 12.00	7.60 " 9.60
100	12.50 " 16.00	10.00 " 12.00

We recently had occasion to analyze the cost of power of a plant which was in operation, where a considerable part of the hot water from the condenser was used in the dye house and about 30 per cent of the steam to the high pressure cylinder was taken out at the receiver and used for heating the buildings in winter. This analysis was made by conducting several tests on the plant and also by obtaining information from the station reports and mill books. In this case the gross cost of power was reduced, due to the credits for heat units used in manufacturing by about 23 per cent.

In some plants it is possible to greatly increase these credits by bleeding more steam or even by running non-condensing. In this particular plant to introduce these further refinements would have led to two systems of steam piping in the dye house, as only part of the processes could use exhaust steam, and also it was found that the help in this particular plant were accustomed to using high pressure steam in their machines. Any oil in the manufacturing steam was also objectionable and at the time that the plant was installed, the bleeding of turbines was unfavorably regarded by the turbine builders.

It is interesting to note in connection with the operation of this plant that twelve boilers are run daily, while the steam going to the engine requires the output of only two boilers.

Another manufacturing plant of the same type as the above, where the mill help is accustomed to the use of low pressure steam, is installing a turbine plant where about one-half of the steam power will be obtained from non-condensing turbines and turbines from which steam may be bled. The rest of the steam power will be obtained from condensing turbines, thus giving a very flexible arrangement. Part of the hot water from the condensing machines will be used for manufacturing processes.

Credits to power in this plant will be a great deal more than the above. The actual cost of coal for power will be represented by the work done and the losses in the turbines and piping to and from them, and in such warm water as goes to waste.

While the proportion of the turbines installed in the past which have steam bled from them is not nearly so great as that of the engines, in this section, it would seem that bleeding turbines should prove to have greater advantages than bleeding engines.

1. Because there is probably less B.t.u. loss, due to condensation in a turbine than in an engine.

2. Because the steam bled from a turbine is free from oil, which might soil the manufactured product. This, of course, is not the case with an engine on account of the cylinder oil.

It is very gratifying to see that the turbine builders are coming to realize these facts and are modifying their designs to facilitate this bleeding.

J. C. Parker: The discussion has been so extensive that it does not seem that the author could add anything in closing except to emphasize and possibly explain some of the points on which differences of opinion have arisen.

These very differences of opinion have been a source of disquietude to one of the speakers. To the author, however, it is rather satisfactory to note that these differences have arisen, since they have at the least indicated that the paper does not deal with a subject on which there is so great unanimity as to make a discussion unprofitable, nor does the author feel that these differences are surprising. Human knowledge is always increased by going from the things that we know intimately to the things that are less familiar and in the process there is always a similarity to or differentiation from the things that we have believed in the past, so that it is not surprising that Mr. Moses, whose work has been in one field; Mr. Williams, whose work is in the same field as the author's but in a different locality, and the author, should arrive at somewhat different conclusions as to different data. The author is sure that as we all progress in knowledge, we will come together more and more closely, approaching the limit from many different directions.

It does not seem worth while to discuss in detail the numerical data presented by the various gentlemen who have contributed to the discussion. It is all interesting and valuable when weighed with relation to the point of attack and the inevitable predisposition which in even abstractly scientific work subconsciously influences the observer. That the author's own data is influenced by such considerations he would not for a moment attempt to deny but he is not sure as to the side on which he errs. In the attempt to make the data conservative he would be influenced to find low first cost and low operating cost, while on the other hand, were the wish father to the thought, he would naturally believe that both investment and operating costs are very high.

He does believe, however, that estimates based upon operation over a period of years are more conclusive than test data gathered from a ten or twenty-four hour test when firemen and enginemen are naturally endeavoring to make as good a showing as possible for the plant, and during which it is very hard to accurately determine banking coal and impossible to ascertain supplies, repairs, etc. Similarly it is almost impossible to make an estimate of the first cost of a plant from an addition of the constituent items, in which even a skilled engineer may readily fail to incorporate a mass of small but, in the aggregate expensive details entering into the plant. In so many cases has the author found the actual facts to be widely variant from pre-estimates and from short period test data that he is forced regretfully to confess the inadequacy of such methods.

The author would like to direct attention again to the fact that, while apparently high, all the installation figures given in his paper are from actual quotation and the operating costs are based on observation of a very large number of plants actually run for a period of years. In connection with the latter it should be noted that adequate book-keeping is distinctly the exception rather than the rule and that where bookkeeping has been accurately carried out, the cost of repairs, etc., is invariably shown to be much higher than where the usual and slipshod methods have been pursued.

Considerable discussion has attached to the operation of the marginal principal with reference to both managerial time and fixed investment.

While it may betoken bad management, the author's observation has been that, whether they should or not, managers give a very great amount of time to the operation of their engine plants. It may be that this in part arises from the eternal boy in even the most serious minded adults, and it may be that an able man could not be employed on even an ample salary to devote his life to the supervision of 200 or 300 h.p. of apparatus.

That such time should be charged with only its fair salary value seems to the author a fallacious contention. He does not believe that the owner of an establishment would employ a $10,000 manager unless the owner expected to make or to save two or three times that amount as a justification for employing him, and it certainly involves a loss of whatever would have been gained when such a manager's time is diverted to other activities without producing such a gain.

The same reasoning applies to capital invested. Many a time has every business man expressed himself by saying that he cannot afford to put money into a certain venture because he will make so much more by putting it into the venture which he already has. The same reasoning must apply to the details within the business.

Some of the gentlemen discussing the paper have evidently misapprehended the operation of the margin in that they have claimed that there are very few businesses that would pay as big a profit as the author has assessed against an isolated plant. This is perfectly true and applies to the central station business as well as to the industrial and mercantile pursuits. A study of the curve given in the paper will indicate that certain essential factors in the business are, as brought out by Mr. Peck, nonproductive and must, whether one will or no, be taken at a loss in order to put the owner in a position where he can discharge the ultimate functions of the business. As shown by the curve, such features reduce the average profit perhaps much below that obtaining at the margin, which is in itself a constantly decreasing amount.

Reference has been made to the fair profit for the central station. The author agrees with several of the speakers, that assuming an *average* profit of 11 per cent, almost every central station in the country would appear as a charitable institution, but after noting that the average profit is very much lower than the marginal profit we may note one other fact; namely, that the margin of profit is determined by the individual and by the business and is different for different individuals and different industries, being always defined, as noted in the paper, as the most that can be got in any other business of which the promoter has knowledge. The public utilities art being practically a standardized and assured one with relatively small local competition, the proprietors suffer less risk of total failure than do the proprietors of an industry that may be more or less new and untried and where local or outside competition, operating through the channel of transportation and changes in the public whim, may at any time precipitate financial disaster. This fact is illustrated by a reference to the conditions obtaining in stock exchange quotations of industrials and of railroad securities.

That the amortization fund should not bear interest at the normal interest rate plus the fair profit rate seems to the author to be an entirely correct proposition, since while the amortization fund may be reinvested in the business, it is simply a case of the firm borrowing money for the business from its own amortization fund at the market rate, and while such borrowings may and properly should pay the same fair profit as any other borrowed money, this extra earning is properly creditable to the business as an inducement for borrowing and investment.

Aldis E. Hibner: In concluding the discussion which has been so valuable in demonstrating the different view points of those dealing with industrial power costs, I wish merely to explain my own point of view more fully where it seems to have been misunderstood by the various speakers.

In the first place, mention has been made concerning the selection of an 80 per cent load factor. It is obvious that some basis for calculation must be assumed and this value was selected as fitting the case of a shoe factory from which my example was derived. As pointed out, this is higher than can ordinarily be obtained and for that reason a curve was plotted in Fig. 3 giving the cost of power for any other load factor.

Mr. Arthur Williams in his discussion has assumed that the heating load was 62 h.p. If reference is made to Fig. 1 it will be seen that the average heating load is 44 h.p. As to the amount of coal required for heating, the conditions vary so enormously that each problem requires special treatment. For the particular case the writer had in mind in his example 475 tons for the heating season is not excessive. The object of charging full time for a fireman for heating the building is given in the paper. We can only charge against the cost of power the actual additional expense incurred by its generation.

The example of power costs from fifteen plants given by Mr. John H. Norris might be of considerable value if given more in details. As the figures stand at present, however, they are of little value as in numerous instances the price of the fuel is not given. In the case of Plant No. 12 the fuel cost is taken at 0.3 cent per kw-hr. whereas the results of the tests given in the plant show a fuel cost of 0.47 cent in one case and 0.69 cent in the other.

Also in the case of Plant 15 the cost of fuel is taken at 0.17 cent in one place whereas in the results of the test in this plant the fuel cost is given at 0.42 cent. Furthermore, only 10 per cent is figured to cover the fixed cost of a gas engine plant and this should, in the writer's opinion, be raised to at least 15 per cent.

In answer to Mr. Tillman's question regarding the items of coal for night heating and for banking, I would say that the coal for night heating is the additional amount required for heating the building during the winter months over and above what would be required for simply banking the boilers over night.

In conclusion I wish to emphasize what Mr. Jackson has said regarding the imperative demand for detailed figures in comparing power costs. Much data that would be very valuable is made worthless by lack of detail on points of vital importance.

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FLYWHEEL LOAD EQUALIZER

BY W. N. MOTTER AND L. L. TATUM

The use of flywheels to equalize the loads on steam engines, punch presses, rolling mills and other machinery of this class has been known for years but its use in connection with electrical machinery for operating hoists, steel rolls, etc., is comparatively new.

Peak loads of relatively long duration are universally handled either direct by the generating equipment or with the assistance of storage batteries, but for conditions where the peak load is of short duration, the flywheel equalizer is cheaper, more efficient and better suited.

For short peak loads, such as are met with on rolls, punches, planers, etc., where non-reversible motors are used, the flywheels are direct-driven by the motor on which the load comes, and the flywheel transforms only the energy of the peaks. Where the driving motor must be reversible, such as in steel mills, electrical hoists, etc., the flywheel is necessarily carried by some other device, usually a motor-generator which acts as a link in the transmission system, and whether the supply be direct or alternating current, the energy is all transformed from electrical to mechanical, and from mechanical back again to electrical.

It is the purpose of this paper to give data from an installation now in operation, which is a typical example of conditions existing in many parts of the country where reversible motors are used, and in which a flywheel may be used to transform the energy of the peaks only. The installation used as an example is an ore hoisting equipment. The load to be handled consists of three ore bridges, each equipped with three 125-h.p., one 75-h.p., and one 5-h.p., 500-volt motors, aggregating 1365 h.p.

The capacity of these hoists is 10,000 tons of ore in ten hours. The power is obtained from the feeders of a 550-volt trolley system some 1,100 ft. (335 m.) from the generating station.

Graphical records taken to determine the number and size of peak loads in a certain given time showed the following results:

Record No. 1. Highest peak 1,200 amperes for ten seconds; about one peak of 1000 amperes every five minutes. Most peaks average 600 amperes.

Record No. 2. Highest peak 1,400 amperes; about one peak reaching 1,100 to 1,200 amperes every five minutes. Average peak about 850 amperes.

Record No. 3. Maximum peak 1,600 amperes, other peaks of 1,400 amperes about once every 15 minutes, most of the peaks not exceeding 800 amperes.

Record No. 4. Maximum peak 1000 amperes, most peaks not exceeding 700 amperes.

The ratio of average amperes to maximum amperes ranges from 17 to 25 per cent and the maximum kilowatt demand is 880. When unloading wet ore this ratio is reduced and the maximum demand naturally increased, the loads being sufficient at many times to open a circuit breaker which was set at 2000 amperes.

Analysis of the above records show a recorded maximum load of 1600 amperes, while the tripping of the circuit breaker when handling wet ore shows 2000 amperes, or 1,100 kw. These peaks were necessarily considered in determining the demand charge for service, but inspection of the record indicated an average load of only 300 to 400 amperes, with a maximum of 600 amperes, or 330 kw., if the short peaks could be eliminated or absorbed.

The problem then was to obtain a method of keeping the peak loads down to 600 amperes and thereby obtain a maximum demand charge on this basis. To secure this reduction, three methods were offered, namely, a storage battery, motor-generator sets, and an idle motor with flywheel floating on the 550-volt line.

Taking the cost, weight, and floor space of the idle motor equipment as unity, the storage battery proposition would cost initially 3.9 to 4.6 depending on type of regulation. The maintenance of the battery would be higher than would be expected either of the motor-generator set or the floating flywheel motor set. Of course, the battery in itself would be free from moving parts, but a booster would be necessary in connection with it.

Again, it would be necessary for this booster to respond only in proportion to the change in amperes required by the hoists and be unresponsive to variation in the railway load which is on the same feeder. The battery would, however, transform only the peak loads, the average being carried directly by the feeder. The efficiency of the double transformation, including the booster losses, was estimated at not over 66 per cent.

The motor-generator set of 2,000 amperes, or 1100 kw., peak loads would cost on the above basis about 1.13. The weight, including the flywheel, would be about 1.5, and the efficiency at 2,000 amperes would be about 81 per cent. Under normal conditions, with a load of zero to 1000 amperes, averaging 300 amperes, the efficiency of the set would approximate 72 per cent, or a constant running loss of 65 kw. The regulation of the set would be excellent, using a compound-wound motor and compound-wound generator, and would require no auxiliary apparatus to secure this regulation. It would not have any great tendency to assume any part of the railroad load.

The third proposition, namely, the motor with a flywheel floating on the line would cost 1. The function of this machine would be quite similar to that of the storage battery in that it would furnish the energy for the peak loads and there would be no transformation of the normal energy absorbed by the hoist motors. The constant running loss would be about 38 kw., or for an average load of 300 amperes, an efficiency of 80 per cent.

This form offered advantages over the battery of lower first cost, higher efficiency, lower depreciation, greater simplicity of regulation and less floor space. Over the motor-generator it offered the advantages of lower first cost, higher efficiency and less weight and floor space. It was, therefore, decided to install a motor with a flywheel floating on the line, and specifications were drawn up requiring that no more than 600 amperes be drawn from the line when a peak load of 2000 amperes was delivered to the hoist. This meant that the flywheel must be of such capacity as to deliver 1,400 amperes at 550 volts for 15 seconds.

The apparatus installed consisted of an interpole motor of 300-kw., 550-volt, 600-rev. per min. rating for normal capacity, with an over-load capacity of 850 kw. for 15 seconds, with a drop in speed of 22 per cent. The flywheel was a solid cast steel disk nine ft. (2.7 m.) in diameter by 15½ in. (39.3 cm.) face.

The armature and rotating parts weigh 47,275 lb. (21,442 kg.), which at 600 rev. per min., represents 25,700,000 ft-lb. of energy stored. (ft-lb. = kg-m. × 7.233). At 470 rev. per min. the energy stored equals 16,000,000 ft-lb., or with a 22 per cent drop in speed there would be delivered 9,700,000 ft-lb. of energy. If this change in speed took place in 15 seconds, the energy delivered would be 875 kw. or 1600 amperes at 550 volt, or more than the maximum peak required, as shown by the original records.

Fig. 1 shows the flywheel generator set as installed. The flywheel was housed in a sheet steel casing to prevent accident and to reduce the windage loss. This windage loss even on a smooth surface becomes a factor when a peripheral speed of 17,000 ft. (5181 m.) per minute is reached. The reduction in windage loss, due to the cover being on, amounted to 2.1 kw.

FIG. 1.—Flywheel generator set

Fig. 2 is a schematic diagram of the main electrical connections. The motor was compound-wound, the series winding being on the load side of the circuit between the hoist and the motor. This allowed operation as a shunt motor when the flywheel was taking energy from the feeder, but when delivering energy to the hoists the machine acted as a compound-wound generator. Since the hoists took some, or the average, current directly from the feeder, which would, at all times, partially energize the series winding, a magnetic switch *S S* (Fig. 2) was installed to short-circuit it. A current relay, *C R* (Fig. 2) controlled the magnetic switch opening the short-circuit around the series winding at a hoist current of 400 amperes. At 400 amperes the series winding was suddenly energized and the counter e.m.f. of the machine raised enough to cause it to deliver energy to the circuit, instead of absorbing energy from it. The series winding was so adjusted that the delivered energy was approximately proportional to the current in the series coil, making the machine take the desired proportion of the total load. When the demand dropped to about 300 amperes the series coil was again short-circuited dropping the voltage, so that the flywheel again absorbed energy.

Fig. 2 also shows the shunt field connection scheme. On account of the approximately constant line voltage, and the variable speed, 470 to 615 rev. per min., it was necessary to adjust automatically the shunt field strength to suit the momentary values of the speed. If the field was too weak, the motor current or rate of absorbing energy would be too high, while if generating, the voltage would be too low to allow the machine to take its proper proportion of the total. Either case would throw heavier loads on the feeder. To correct for this, current relays, R_1 R_2 R_3, etc., (Fig. 2), were connected in the feeder and arranged to commutate resistance in series with the shunt field. These were set to operate at different values, from 400 to 600 amperes. Below 400 amperes, that is, below the average load, all relays were open, and weak field existed, tending to give maximum speed to the flywheel. Above 400 amperes feeder current some relays closed, strengthening the field, and reducing the motor current, or increasing the generated current, depending on whether the series coil was in action or not. Under a sustained peak the flywheel would slow down gradually and the field would strengthen gradually until with the wheel at its

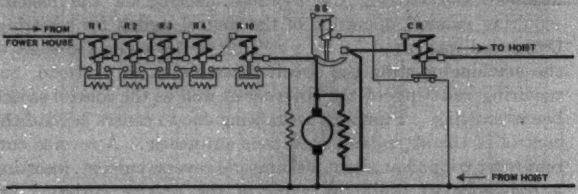


FIG. 2.—Schematic diagram of principal connections

lowest speed, 470 rev. per min., and maximum field strength, the feeder would be supplying 600 amperes.

The function of the shunt field regulation was therefore to maintain the voltage of the flywheel machine approximately equal to the feeder voltage under all conditions of speed, while the auxiliary series field and its switch and relay changed the characteristics from those of a motor to those of a generator as needed.

As part of the control system, a current limiting relay self-started was provided to automatically take care of the necessarily slow start, and several safety features were added. The troubles to be anticipated were overload, overspeed, and pumping back into the feeder in case of lowering or failure of supply voltage. The first two would be local troubles, needing investigation of the attendant before restarting. Overload was cared for by automatically cutting the flywheel machine off the feeders, requiring manual operation of the control switch for resetting. Overspeed was cared for by a centrifugal device on the shaft of the machine opening the circuit the same as an overload, but requiring resetting of the governor as well as the control switch before starting. Pumping back, being due to causes beyond the control of the attendant, was made automatic. A reverse current relay tripped at about 200 amperes reverse current, inserting a resistance to limit the value of the reverse current. On restoration of line voltage, the current would flow in the normal direction, the relay reset, and the flywheel automatically restart, or regain speed.

Fig. 3 is the detail connection diagram of the system.

After the system was installed and adjusted, provisions were made for taking simultaneous graphical meter curves on the feeder and on the load circuits. These curves are shown in Fig. 4. The upper curve, noted as accelerating curve, shows the cycle through which the machine passes when started up. Due to the high voltage the initial surge of the current exceeds the 600 limit slightly, falling off, as the motor accelerates, to 275 amperes after 1¾ minutes. The first accelerating switch then closes giving a second surge of 500 amperes. The current then gradually falls for about 1¾ minutes when the second switch comes in, etc. It is interesting to note that after the fourth peak the current line becomes wavy due to the voltage fluctuation with but little resistance in the circuit. The fifth peak is caused by the closing of the last switch putting the armature directly on the

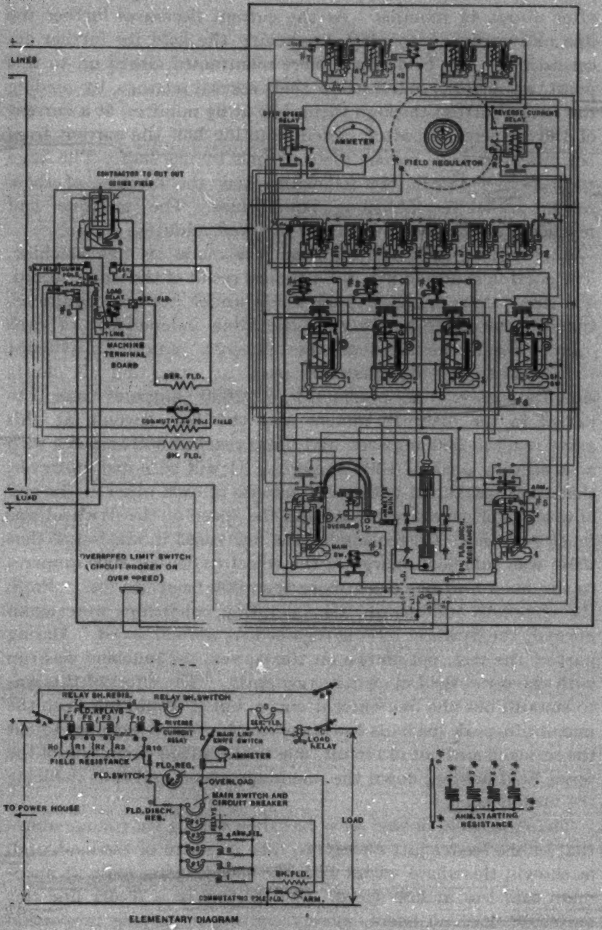
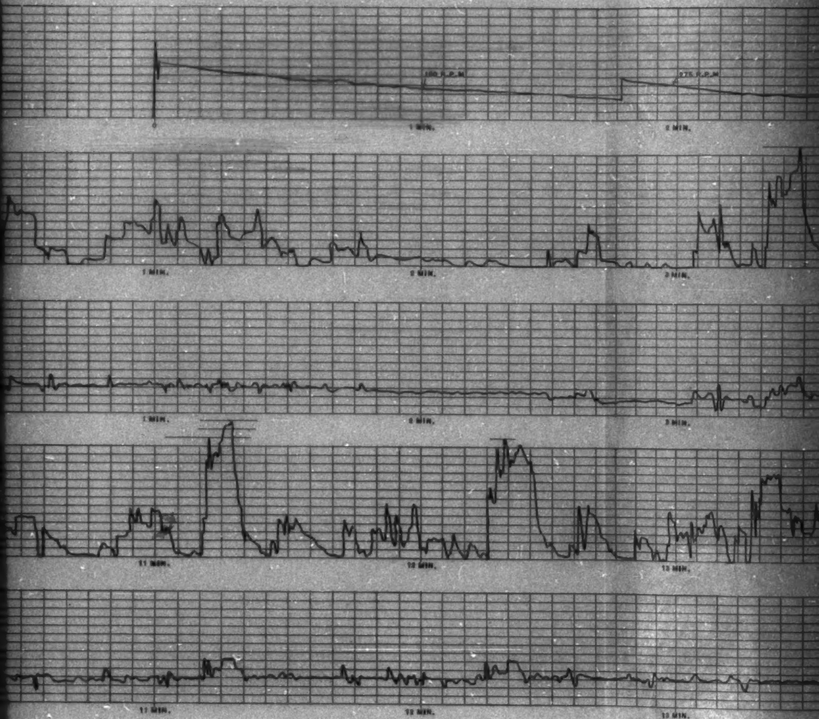

LINES
CONTRACTOR TO CUT OUT SERIES FIELD
LOAD RELAY
SER. FLD.
MACHINE TERMINAL BOARD
COMMUTATING POLE FIELD
SH. FLD.
LOAD
OVERSPEED LIMIT SWITCH (CIRCUIT BROKEN ON OVER SPEED)
OVER SPEED RELAY
AMMETER
FIELD REGULATOR
REVERSE CURRENT RELAY
OVERLOAD
MAIN SW.
ARM.
RELAY SH. RESIS.
RELAY SH. SWITCH
FLD. RELAYS
F1
F2
F3
10
REVERSE CURRENT RELAY
MAIN LINE KNIFE SWITCH
SER. FLD.
LOAD RELAY
R0
R1
R2
R3
R10
FIELD RESISTANCE
FLD. REG.
AMMETER
FLD. SWITCH
OVERLOAD
MAIN SWITCH AND CIRCUIT BREAKER
TO POWER HOUSE
FLD. DISCH. RES.
RELAYS
ARM. RES.
LOAD
SH. FLD.
COMMUTATING POLE FLD.
ARM.
ARM. STARTING RESISTANCE
ELEMENTARY DIAGRAM

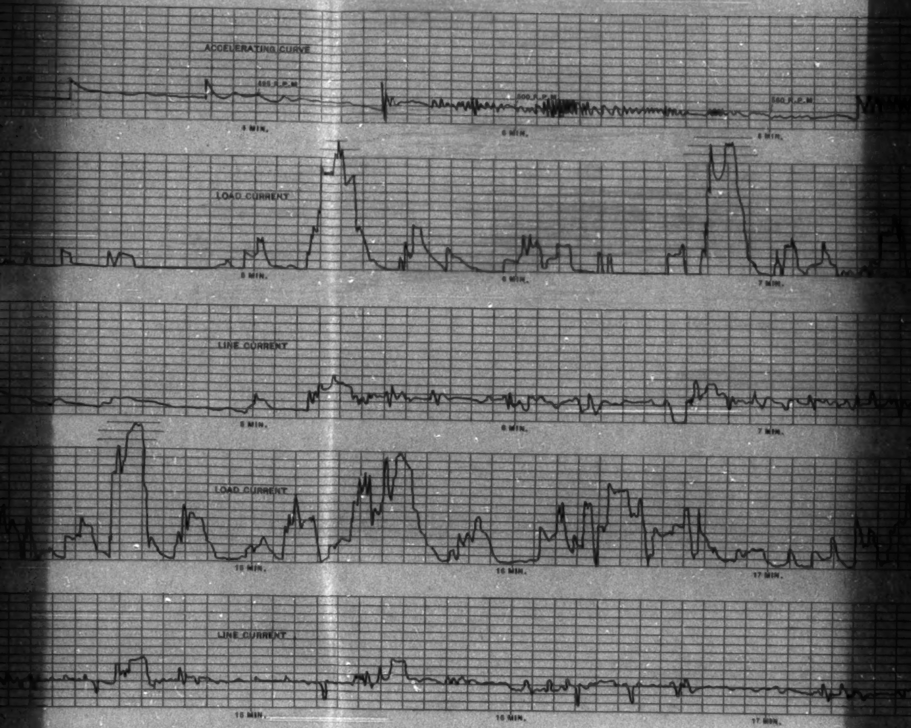
FIG. 3.—Detail connection diagram

line. At this point the speed is 470 rev. per min., which comes after about 4½ minutes. As the current decreases further the line relays come into play, weakening the field for further acceleration. The field relays were maintained closed up to this point, at currents much below their normal settings, by sending the entire current through them, but at 6½ minutes, at a current of 180 amperes, a switch closed shunting half the current from the relays so as to reduce their settings by one half. The large oscillations immediately following show the hunting of these relays while reestablishing equilibrium. The machine had reached its full speed at the end of seven minutes.

A record of 2½ hours duration was made on this machine. The portion shown in Fig. 4 is a typical result of the entire record. The first three minutes were made under normal conditions, that is, the three hoists were operating independent of each other. From the third to the sixteenth minute an attempt was made to get the maximum peak by operating all hoists simultaneously. A maximum of 1600 amperes was obtained in the fifteenth minute and the line current at this point reached 600 amperes, and again reached 600 amperes with a succeeding peak of 1300 amperes. It will be noted, however, that these peaks fall within one minute of each other at the end of a series of excessive peaks, and the speed of the flywheel was much reduced. Correcting for the low speed it was found that there was sufficient energy in the wheel to deliver 2000 amperes to the hoist and not draw more than 600 from the line. From the sixteenth minute on, the operating conditions were again normal, the flywheel having regained its normal speed. During part of the test, not shown on the curves, the machine was run with the series field in circuit constantly. The effect of this was to smooth out the line current curve, but it would not keep the maximum peak loads as low as when the relays were set to cut the series in and out of circuit, due to the added excitation of the series field holding down the maximum speed and thus reducing the stored energy.

The regulation of this set is based on raising its voltage above that of the feeder just enough to take its share of the load, and, as shown, this share varies with the speed, being more at maximum and less at low speed. On the end of a feeder line this variation does no harm, merely shifting a varying proportion to the power house. If, however, the set were installed in the power house with no line drop between the main generators and


0
150 R.P.M.
275 R.P.M.
1 MIN.
2 MIN.
1 MIN.
2 MIN.
3 MIN.
1 MIN.
2 MIN.
3 MIN.
11 MIN.
12 MIN.
13 MIN.
11 MIN.
12 MIN.
13 MIN.



-Graphical current record of flywheel load-equalizing generator

the flywheel set, this variation would probably cause the flywheel to take the entire station load at maximum speed, while at minimum speed it might take none. With over-compounded generators this would probably be true, but with a drooping characteristic of the main generators the trouble would be reduced. These conditions, however, make it very doubtful whether successful operation could be obtained with the set installed in, or very close to, the main generating plant. If used with a synchronous converter, which would give the necessary drooping characteristics, such a set could be advantageously used in the power house with alternating-current generators as the main source of supply.

The action of the set has been very satisfactory from a mechanical and electrical standpoint. From a financial point it has also been exceptionally good, as shown by the following table which gives the cost of current and the ore handled by the dock for corresponding months in the last three years. In 1908 the flywheel set was not in operation. In 1909 and 1910 it was used.

	1908			1909			1910		
	Tons	Cost	Per ton	Tons	Cost	Per ton	Tons	Cost	Per ton
Sept......	32336	$820	0.0255	82097	$652	0.0080	67715	$560	0.0083
Oct.......	39900	910	0.0227	96183	592	0.0062	54558	510	0.0094
Nov.......	36175	870	0.0240	94614	720	0.0077	35287	480	0.0136

Whether or not the installation of such apparatus is warranted requires a careful study of load peaks as well as rates. Where the definition of "peak" as used in determining rates is a maintained rate for 15 minutes or more, it would be manifestly unwise. In fact, a maintained rate of even 600 amperes for 15 seconds is not shown on the load chart, though an average for 15 seconds would be found much higher than 600 amperes. A five-second peak of 1100 amperes, a three-second peak of 1300 amperes, and a momentary peak of 1600 amperes are found.

As an example, the rates applying around Duluth may be applied to this chart. The demand rate may be based on 40 per cent of a momentary peak, or 50 per cent of a one-minute peak, or 66⅔ per cent of a three-minute peak, or the net value of a five-minute peak. The 40 per cent momentary value is largest, and is 640 amperes or 352 kw. The other peaks would all be zero, as at no place on the chart is found a full minute without a zero reading. The demand charge, or reservation charge, is $1.00 per kw. per month on the maximum rate adjustment above, or $352 per month. The current charge is made up of two items; seventy hours at demand rate and $0.0125 per kw. hr., or 24,640 kw-hr. at $0.0125, or $308. The balance is at the rate of $0.006 per kw-hr. On the assumption of 260 hours per month at 250 amperes, or 137½ kw. average, the kilowatt-hours would be 35,750, leaving a balance of 11,110 kw-hr. for which the rate is $0.006 or $66.66, making a total of $726.66.

With the flywheel, the integrated load would be increased to say 300 amperes or 165 kw., or 42,900 kw-hr. The demand would be 40 per cent of 600 amperes or 240, or on a five-minute net rate would be 300 amperes or 165 kw. The latter would, therefore, be the base rate. The demand charge would then be $165. The first item of charge 165×70 equals 11,550 kw-hr., at $0.0125 or $144.37. and the remaining 31,350 kw-hr. at $0.006 equals $188.10, or a total of $497.47, a reduction of approximately $230 per month. If, however, the hoist stood idle for a month with no current consumption whatever, the presence of the set would mean a reduction in the demand charge from $352 to $165, or a saving of $187.

In cases where the supply is alternating current, direct-current motors can be used with a synchronous converter, and a direct-current flywheel set, with the transformers and converter having only capacity for slightly more than the integrated load, while the flywheel machine has momentary capacity for the difference between that rating and the peaks. Compared to an induction motor-generator the overall efficiency would be 81 percent for the rotary and the flywheel machine, as against 81.5 per cent for the induction motor flywheel set. The power factor would be unity as against about 94 per cent. The cost would be about as one to 1.03 in favor of the converter. The relative weight of the converter and flywheel set to the motor-generator set with a flywheel would be one to 1.13. A storage battery could hardly be considered in this case.

From the foregoing it appears that for short peak loads, especially where the ratio of the peak to the average load is large, the type of installation described is advantageous on account of low first cost, high efficiency, ease of regulation, ease of protection against abnormal conditions, comparatively light weight and small floor space necessary.

A direct-current to direct-current motor-generator flywheel set would have the advantage of simpler regulation, but would cost more, be less efficient, and heavier and bulkier.

A flywheel motor-generator set having an alternating-current motor wound for use without transformers and a direct-current generator compares very favorably with the motor flywheel set with the use of a converter and transformers.

A storage battery would have no point of advantage but would be higher in cost, lower in efficiency, more complicated in regulation, higher in maintenance, heavier and bulkier. In cases where the maximum peaks were of long duration, it would, however, have advantages to more than offset these. It appears also that where the demand charge is based on peaks of more than 15 seconds, there would be nothing gained with a load of the type described, by the installation of any load equalizing device, unless the line losses were so bad as to make the improvement of service warrant the expenditure.

A paper presented at the 261st Meeting of the American Institute of Electrical Engineers, New York, April 14, 1911.

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COMMERCIAL TESTING OF SHEET IRON FOR HYSTERESIS LOSS

BY L. T. ROBINSON

The desirability of being able to determine quickly and with reasonable accuracy and cost the hysteresis and eddy losses in sheet iron for use in transformers and other alternating current apparatus is fully appreciated and need not be discussed. The arrangements that have been devised by various workers along this line, some of which have been described,* evince the fact that the subject has received much attention from time to time and that the methods of testing samples by means of ballistic galvanometer or by wattmeter test on complete apparatus are not entirely satisfactory.

The purpose of the present paper is to discuss the question generally in the light of practical requirements of the maker or user of sheets and to describe means which have been devised as a result of many years experience in meeting shop requirements for making the regular tests.

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*I. Epstein, *Electrotechniche Zeitschrift*, Vol. 21, No. 16, April 19, 1900, page 303.

E. Gumlich and P. Rose, *Electrotechniche Zeitschrift*, page 403, Vol. 26, No. 17, April 27, 1905.

J. A. Mollinger, *Electrotechniche Zeitschrift* Vol. 22, No. 18, 1901, page 379.

Various abstracts from the Proceedings of the Vereindeutcher Elektrochniker E. T. Z., page 520 No. 20, May 19, 1910; page 740 No. 28, July 13, 1910; page 826, August 11, 1910; page 684, Aug. 20, 1903; page 720, July 27, 1905; page 801, Sept. 19, 1901.

National Bureau of Standards Reprint 109, Testing of Transformer Steel, by Lloyd and Fisher.

Battie Electrician, Vol. 62, page 136, 1908.

J. W. Esterline, Proc. Am. Soc., Testing Materials, Vol. 8, page 190, 1908.

For the purpose of showing the general degree of accuracy that can be obtained by the methods described, results are given of tests made by ballistic galvanometer as well as by wattmeter methods using identical samples.

The general requirements may be summarized as the following:

1. The accuracy of the test results should be such that the error obtained will be small in comparison with the unavoidable error in making the test sample represent the actual average quality of the material.

2. The dimensions, weight and treatment of the sample should be such that the results may represent the average material from which they are taken as nearly as possible.

3. If without sacrificing unduly other desirable features samples can be used that will be uniform in dimensions, weight, and method of preparation with those used by others, such standard samples should be employed.

4. The entire operation of preparing and testing samples and recording results, should be quickly accomplished and at minimum expense for material and labor.

5. The testing should not require the services of specially trained experts or the use of delicate special instruments.

All the above conditions are not completely met by any apparatus, but we can perhaps make the best progress with the general discussion of the problem from the point of view being presented, by describing two complete sets of apparatus which are being used.

The first uses a one-pound (0.45-kg.) sample made up of strips 10 by ½ in. (25.4 by 1.27 cm.) in dimensions and designed to meet to the fullest possible extent the fourth requirement. The arrangement can be easily used to test the standard sample referred to under requirement three.

The second arrangement was designed specially to meet requirements 1, 2, 3 and 5 using a sample 3 by 50 cm. and weighing 10 kg. (22 lb.) The whole arrangement adheres very closely to the Epstein apparatus already referred to and uses the same size sample.

Discussion of the relative advantages and disadvantages of the two arrangements together with any comparisons with other methods will be deferred until after they have been more completely described and relative test results which have been made on actual samples are given.

HYSTERESIS TESTING OUTFIT FOR 10 BY ½-IN. SAMPLES

The set completely assembled is shown in Fig. 1. The method employed is that of measuring the watts lost in a straight sample using sensitive reflecting dynamometers as wattmeter and voltmeter. For convenience this set is arranged to test samples having a weight of one lb. (0.45 kg.) in a solenoid with open ends returning all the magnetic flux through the air. The height of sample required is about ¾ in. (19 mm.). On account of the fact that the flux is returned through the air the density *B*, in the core varies from a maximum at the center to a minimum value at either end of the sample.

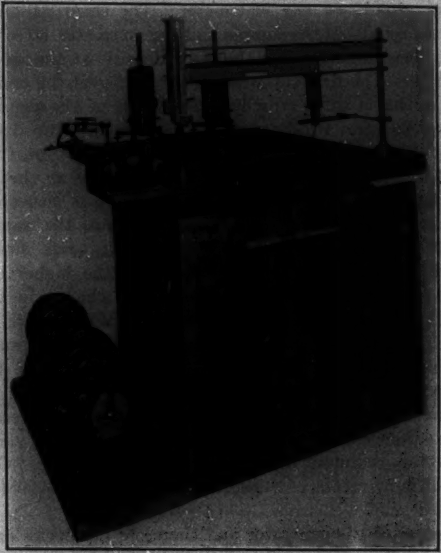

FIG. 1.—Hysteresis testing outfit

The magnetizing current is furnished by a small motor generator set shown in the illustration which is driven from a storage battery. The frequency used is ten cycles at the present time and the density is equivalent to $B=10,000$ (6⅔ cycles was formerly used when tests were made at $B=5,000$). A low frequency was chosen to reduce as much as possible the eddy current loss in the sample so that there would be no serious error in the final result. In practice the eddy losses are usually deducted as a definite fixed sum for a given kind and thickness of material being tested.

There are three windings on the solenoid in which the sample is placed, one to magnetize the sample and one to supply the potential circuit of the wattmeter. The third winding surrounds the middle of the sample and the voltmeter is connected to this, thus determining the flux density at the middle of the sample. The first two windings project over the end of the sample so that a small error in the position of the sample with reference to the windings will produce no error due to a different distribution of flux in the bundle of strips. During a test this voltage is adjusted to give a density at the middle of the sample which will give a hysteresis loss corresponding to the loss with a uniform density throughout the sample of $B=5,000$ or $B=10,000$. The smaller density was first used (from 1897 to 1909) and this was changed to the higher density for tests made since the latter date. The change in density was made so that the test results would conform more nearly to the changed conditions of use and to make the results obtained more readily convertible into terms that could be directly compared with results obtained by other test methods.

The terminals of the magnetizing winding are connected directly to the generator and the exciting current is varied to produce the required deflection on the voltmeter. Current regulation is by means of a rheostat and slider in the field winding of the small generator.

The speed of the generator and therefore the cycles are held constant at the proper value during the test by observing the indications of a liquid tachometer also shown in the illustration. The adjustment of motor speed is made by a rheostat in the motor field. Fig. 2 shows the wiring diagram of the complete arrangement of Fig. 1.

The scales of the wattmeter, voltmeter and tachometer are so arranged that a single observer can conveniently read all of them and record the results without changing his position.

The proper voltage to be used on the sample is determined by weighing it on a special balance shown in Fig. 1 at the left hand back corner at the top of the pier. This balance is graduated with scales based on a density of 7.8 for standard iron and 7.5 for alloyed iron. These scales connect the voltage with the weight of the sample for both densities. A third scale gives the multiplier to be used for correcting the wattmeter reading to give results for a sample weighing exactly one pound.

The nearest number of strips required to make up one pound is chosen in weighing so that this multiplier is very near unity.

The wattmeter scale is either graduated to read directly in watts per pound at one cycle per second, total loss in the sample, or this quantity is obtained from a table. The graduation or the table is so arranged that the loss in the volt coil of the wattmeter and in the voltmeter is deducted. As the eddy loss is different for different kinds of material this is deducted from the final result instead of being corrected for in the graduation of the wattmeter scale or in the table.

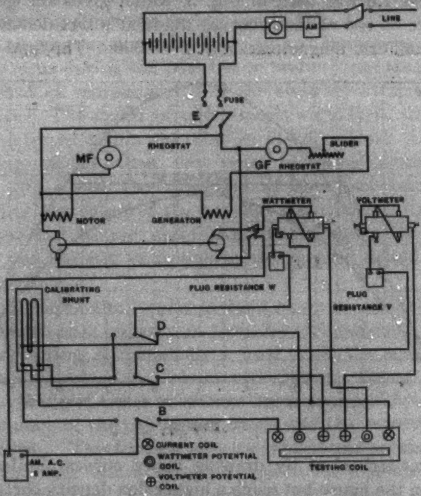
LINE
AM
FUSE
E
RHEOSTAT
MF
GF
SLIDER
RHEOSTAT
MOTOR
GENERATOR
WATTMETER
VOLTMETER
CALIBRATING SHUNT
PLUG RESISTANCE W
PLUG RESISTANCE V
D
C
B
AM. A.C. 5 AMP.
⊗ CURRENT COIL
◎ WATTMETER POTENTIAL COIL
⊕ VOLTMETER POTENTIAL COIL
TESTING COIL

FIG. 2.—Connections of hysteresis testing outfit

The determination of the voltage and number of turns on the volt coil required to produce a magnetization of the sample equivalent in hysteresis loss to that produced by uniform magnetization throughout the sample was determined as follows: Several samples were wound with exploring coils at various points along their length (usually 21 coils were employed) and the samples carrying these exploring coils were inserted in the testing coil and the flux densities or *B* values were plotted as ordinates using the distances along the samples as abscissæ.

The ordinate corresponding to each abscissa was then raised to a power corresponding to the hysteresis loss exponent and the curve replotted. The average of this last curve was used to determine the voltage and number of turns corresponding to that which would result from a uniformly magnetized sample. Exponent 1.6 was used in Fig. 3, which gives the general appearance of one of these curves made at a flux density equivalent to uniform magnetization at $B = 8{,}000$. The final determination was arrived at by drawing many curves similar to that shown in the figure but using a higher flux density corresponding to $B = 10{,}000$. The numerous minor details relating to the complete experiments would not be of interest here. It is sufficient to say that a coil located at the center of the sample requires a voltage related to that for a uniformly magnetized sample as 1.3 to 1.

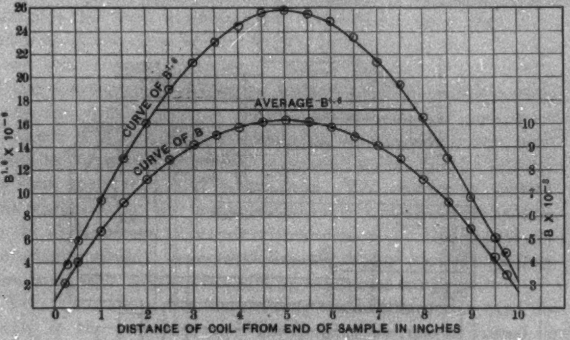

FIG. 3.

For confirmation of this result see.[1,2]

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[1] "A method of Determining Magnetic Hysteresis Loss in Straight Iron Strips." By J. A. Fleming, Electrician, (London), June 25, 1897, Vol. 39, No. 9, page 283.

[2] "On the Distribution of Magnetic Induction in Straight Iron Rods." By J. L. W. Gill, B.A. Sc. Phil. Mag. S. 5, Vol. 46, No. 282, Nov. 1898, pp. 478, 494.

Consideration of the problem led to the conclusion that if a method of testing using samples in which the distribution of the flux density was so far from uniform could be used at all the proper place for the volt coil was at the center of the sample. The sample need not then be very accurately placed with reference to the volt coil. The results obtained are practically much more exact and theoretically as good as if the volt coil is placed at a point where the turns correspond to the number required for uniform mangetization.

The samples to be tested are inserted into the testing coil and withdrawn from it by means of a wooden holder which can be seen projecting from the testing coil in Fig. 1.

From an enormous number of tests that have been made by this apparatus during the past ten or twelve years the following are selected as representative of the accuracy attainable with the device. The speed of operation is very high, 40 samples have been tested within five minutes at an expense per sample for testing of less than two cents, including punching, annealing, etc., and the recording of the final results. In considering the value of the various arrangements that have been used for testing sheet iron commercially the extreme rapidity and low cost of testing by this method should be given some weight.

Table I shows the results of tests made on several samples with ballistic tests on some of them for comparison.

The reflecting dynamometers used with the small set are calibrated by means of a shunt and ammeter shown in Fig. 2 and the volts and watts on the instruments are computed from the resistance of the calibrating shunt and the current read by the ammeter. This forms a very convenient and accurate means of checking the instruments in place at the frequency of test. The calibrating shunt is divided into two parts having resistances suitable for checking the voltmeter and wattmeter and using only one ammeter for both measurements. It is customary to make such a check once each day or before each set of tests.

IRON TESTER FOR 10-KG. SAMPLES 50 BY 3 CM.

This apparatus is shown completely assembled in Fig. 4. The testing coil or sample holder is shown in a later form in Fig. 5. The complete equipment comprises, besides this sample holder, a vibrating-reed frequency indicator shown on the left of table and a portable wattmeter, voltmeter and ammeter of suitable capacity and quality to make the necessary electrical measurements with the required accuracy. The ammeter is not necessary. The diagram of connections is shown in Fig. 6.

The details of the testing coil shown in Fig. 5 are as follows:

TABLE I
HYSTERESIS TESTING OUTFIT
WATTS LOSS IN SAMPLES 10 BY ½ IN. WEIGHING 1 LB.

0.014" iron $B = 10{,}000$

Sample No.	Kind of iron	Total loss at 10 cycles	Eddy loss at 10 cycles	Hys. per cycle at 1 cycle per sec. by separation	Hys. per cycle at 1 cycle per sec. by subtraction	Hys. per cycle at 1 cycle per sec. by ballistic	Per cent variation hys. by separation from ballistic	Per cent variation hys. by subtraction from ballistic	Epstein equivalent total watts per lb. at 60 cycles
1	Standard	0.205	0.042	0.0163	0.0173	0.0163	0	+6.14	1.586
2	"	0.186	0.036	0.0150	0.0154	—	—	—	1.508
3	"	0.186	0.031	0.0155	0.0154	—	—	—	1.537
4	"	0.184	0.032	0.0152	0.0152	—	—	—	1.520
5	"	0.183	0.032	0.0151	0.0151	—	—	—	1.514
6	"	0.168	0.031	0.0137	0.0136	—	—	—	1.430
7	"	0.171	0.029	0.0142	0.0139	—	—	—	1.460
8	"	0.170	0.029	0.0141	0.0138	—	—	—	1.454
9	"	0.172	0.034	0.0138	0.0140	—	—	—	1.436
10	"	0.202	0.034	0.0169	0.0170	—	—	—	1.622
11	Alloyed	0.131	0.024	0.0107	0.0110	0.0108	—0.93	+1.85	0.822
12	"	0.144	0.016	0.0128	0.0123	0.0123	+4.08	0.00	0.948
13	"	0.141	0.019	0.0122	0.0120	0.0123	—0.82	—2.44	0.912
14	"	0.138	0.023	0.0115	0.0117	0.0116	—0.86	+0.86	0.870
15	"	0.137	0.021	0.0117	0.0116	0.0117	0	—0.85	0.882
16	"	0.133	0.022	0.0111	0.0112	—	—	—	0.846
17	"	0.109	0.018	0.0091	0.0088	—	—	—	0.726
18	"	0.141	0.020	0.0121	0.0120	—	—	—	0.906
19	"	0.128	0.025	0.0103	0.0107	—	—	—	0.799
20	"	0.093	0.024	0.0069	0.0072	—	—	—	0.612
21	"	0.093	0.024	0.0069	0.0072	—	—	—	0.612
22	"	0.095	0.023	0.0072	0.0074	—	—	—	0.624
23	"	0.093	0.023	0.0070	0.0072	—	—	—	0.612
24	"	0.089	0.019	0.0070	0.0068	—	—	—	0.588

The eddy losses used in computing column No. 6 are 0.032 for standard and 0.021 for alloyed iron. These are the average values obtained by separating upwards of 100 samples of each kind of iron. The eddy losses used in computing column No. 10 are 0.608 and 0.180 for standard and alloyed iron respectively.

On a wooden frame so built as to avoid warping four solenoids are mounted into which the four parts of the sample to be tested are inserted, each of these has 150 turns of magnetizing winding and a second winding of 150 turns for supplying the voltage to the potential coils of the wattmeter and voltmeter. Total number of turns on each winding 600. These windings are laid on at the same time so that they will have exactly the same number of turns located in the same relation to the sample. By this means a voltage corresponding to the flux wave of the sample is impressed on the wattmeter and voltmeter and complicated corrections for the $I R$ drop and the $I^2 R$ loss in the magnetizing winding are eliminated.* This arrangement has been quite generally adopted by those making wattmeter loss measurements in iron samples and is of the greatest advantage in securing convenient and accurate measurements. The advantages of the arrangement are of increasing value as the tests are made at higher magnetic densities where the $I R$ and I^2R corrections in any kind of winding become larger and where the error due to changed resistance of magnetizing winding due to heating becomes important on account of the large increase of magnetizing current required.

Fig. 4.—Apparatus for testing sheet iron

To protect the ends of the coils hard fibre caps are placed over the ends into which the windings are inserted, these end caps are also used to fasten the solenoids to the frame. The four-part sample is assembled into the windings by placing the first portion of the sample against the fibre block shown in the lower part or right hand corner of Fig. 5. This block is cut in such a way that the joint in the sample is completely exposed to view whether the parts of the sample are inserted by passing around the frame in clockwise or counter clockwise direction.

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*See C. P. Steinmetz, Transactions, A. I. E. E., Vol. 9, 1892, p. 64.

The other three joints require no blocks and all the joints are therefore completely exposed. The samples are clamped in place by the four hinged arms shown extending from the center of the frame and held down by hooks engaging in rollers on the flat phosphor bronze springs below the hinged arms. The form of the hook and the general arrangement is such that the clamping blocks on the edge of the arms are forced down on the ends of the sample with sufficient and definite pressure and still there is no danger of clamping the joints too tightly and therefore increasing the losses in the corners. As compared with the original method of clamping shown in Fig. 4 there is a small but appreciable advantage that shows itself in the ability of the observer to repeat his measurements on a given sample with less variation among individual observations. This is particularly true when the observations are made by one who is not constantly engaged in testing with the device.

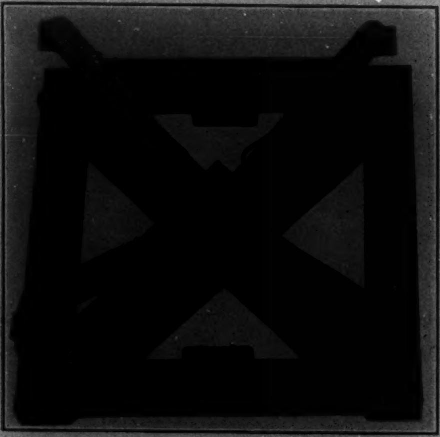

FIG. 5.—Apparatus for testing sheet iron

Before the joints at the corners are crowded together a piece of tough paper or fiber about 0.005 in. (0.127 mm.) in thickness is inserted between the joints. The purpose of this paper is to prevent the exposed end of the laminations being forced into the spaces between those in the adjacent side of the other part of the sample and to prevent the formation of eddy currents at the corners which may not be confined to the thickness of the laminations if the paper is not used. The certainty of the measurements is thereby improved by a small but definite amount over the results which are obtained without the paper in the joints. This improvement is of course accomplished at the expense of some increase of leakage flux at the corners and consequently greater departure from absolute uniformity of flux distribution along the length of the sample, also the conditions imposed upon the wattmeter are more severe as the general power factor is lower. The flux distribution over a section of the sample is more uniform with the paper. The net result is a definite gain in accuracy. The corners are finally forced together by means of a block of wood with a V notch in the end in order to get the joints as firmly together as possible.

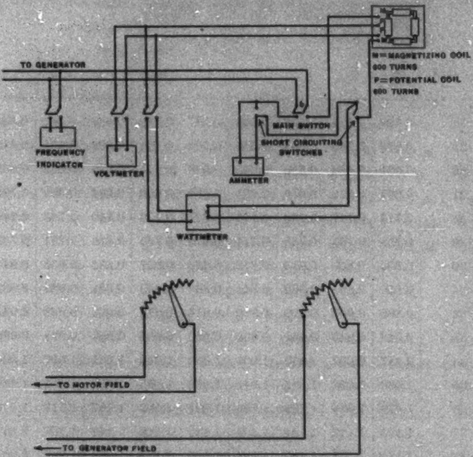
M
M
M=MAGNETIZING COIL
600 TURNS
P=POTENTIAL COIL
600 TURNS
TO GENERATOR
MAIN SWITCH
SHORT CIRCUITING
SWITCHES
FREQUENCY
INDICATOR
VOLTMETER
AMMETER
WATTMETER
TO MOTOR FIELD
TO GENERATOR FIELD

FIG. 6.—Connections of apparatus for testing sheet iron

The voltage and frequency are adjusted to the proper values and the watts lost in the sample and instrument potential circuits is read. For convenience the total loss per pound (0.45 kg.) at 60 cycles is read directly from a table like Table II. The loss may be expressed as hysteresis loss alone by the usual method of separating, using two or more frequencies or generally with a sufficient degree of exactness by deducting the proper amount from the total loss at 60 cycles using the average eddy loss determined from a number of previous separations on the same kind of material. The proper amount of material to be used in the four legs of the sample holder is determined by weighing the material in two portions, usually one cut with and the other across the grain, of 11 lb. (5 kg.) each. The weighing is made to the nearest even sheet and each of the 11-lb. bundles is subsequently divided into two equal parts by balancing the parts against one another.

TABLE II
TOTAL IRON LOSS PER LB. AT 60 CYCLES $B = 10{,}000$
FOR VARIOUS WATTMETER READINGS
FOR 22 LB. SAMPLE ALLOYED IRON (SP. GR. = 7.5)
Resist. of voltmeter = 1800 ohms (approx.)
Resist. of wattmeter = 1800 ohms (approx.)
Resist. of potential coil of apparatus = 7 ohms (approx.)
Voltmeter connected when reading watts

Watts read	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
24	0.529	0.534	0.538	0.543	0.547	0.552	0.557	0.561	0.566	0.570
25	0.575	0.580	0.584	0.589	0.593	0.598	0.603	0.607	0.612	0.616
26	0.621	0.626	0.630	0.635	0.639	0.644	0.649	0.653	0.658	0.662
27	0.667	0.671	0.676	0.681	0.685	0.690	0.694	0.699	0.703	0.708
28	0.713	0.717	0.722	0.726	0.731	0.736	0.740	0.745	0.749	0.754
29	0.758	0.763	0.768	0.771	0.776	0.781	0.786	0.791	0.795	0.800
30	0.804	0.809	0.813	0.818	0.823	0.827	0.832	0.836	0.841	0.845
31	0.850	0.855	0.859	0.864	0.868	0.873	0.878	0.882	0.887	0.891
32	0.896	0.900	0.905	0.910	0.914	0.919	0.923	0.928	0.932	0.937
33	0.942	0.946	0.951	0.955	0.960	0.965	0.969	0.974	0.978	0.983
34	0.987	0.992	0.997	1.001	1.006	1.010	1.015	1.020	1.024	1.029
35	1.033	1.038	1.042	1.047	1.052	1.056	1.061	1.065	1.070	1.074
36	1.079	1.084	1.088	1.093	1.097	1.102	1.107	1.111	1.116	1.120
37	1.125	1.129	1.134	1.139	1.143	1.148	1.152	1.157	1.161	1.166
38	1.171	1.175	1.180	1.184	1.189	1.194	1.198	1.253	1.207	1.212
39	1.211	1.216	1.221	1.225	1.230	1.234	1.239	1.244	1.248	1.253
40	1.262	1.267	1.271	1.276	1.281	1.285	1.290	1.294	1.299	1.303

The following table No. III gives comparison of ballistic determinations with those on the 50 by 3-cm. samples. The ballistic measurements which were made on the various samples for comparison were made by a method substantially like that first described by Vignoles*, and will not be referred to in detail here. Three windings were placed on the samples one for con-

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***Electrician*, (London) May 15, 1891, Vol. XXIII, page 49.

TABLE III
APPARATUS FOR TESTING SHEET IRON
WATTS LOSS PER LB. IN 22 LB. 0.014" EPSTEIN SAMPLES. $B=10{,}000$

Sample No.	Kind of iron	Total loss at 60 cycles	Eddy at 60 cycles	Hys. per cycle at 1 cycle per sec. by separation	Hys. per cycle at 1 cycle per sec. by subtraction	Hys. per cycle at 1 cycle per sec. by ballistic	Per cent variation hys. by separation from ballistic	Per cent variation hys. by subtraction from ballistic
1	Standard	1.725	0.615	0.0185	0.0186	0.0188	—1.59	—1.06
2	"	1.811	0.641	0.0195	0.02005	0.0188	+3.72	+6.40
3	"	1.565	0.617	0.0158	0.0159	—	—	—
4	"	1.735	0.439	0.0216	0 0186	—	—	—
5	"	1.7081	0.586	0.0187	0.0183	—	—	—
6	"	1.465	0.601	0.0144	0.0143	—	—	—
7	Alloyed	0.894	0.186	0.0118	0.0119	0.0118	0.00	+0.85
8	"	0.894	0.156	0.0123	0.0119	0.0122	+0.82	—2.46
*7	"	0.891	0.177	0.0119	0.0118	0.0118	+0.85	0
*8	"	0.891	0.153	0.0122	0.0118	0.0122	0	+3.28
9	"	0.896	0.176	0.0120	0.0119	0.0117	+2.56	+1.71
10	"	0.929	0.197	0.0122	0.0125	0.0124	—1.64	+0.81
11	"	0.920	0.182	0.0123	0.0122	0.0121	+1.66	+0.83
12	"	0.748	0.166	0.0097	0.0095	—	—	—
13	"	0.793	0.199	0.0099	0.0102	—	—	—
14	"	0.883	0.133	0.0125	0.0117	—	—	—
15	"	0.806	0.176	0.0105	0.0104	—	—	—
16	"	0.774	0.180	0.0099	0.0099	—	—	—
17	"	0.738	0.150	0.0098	0.0093	—	—	—
18	"	0.767	0.179	0.0098	0.0098	—	—	—
19	"	0.767	0.167	0.0100	0.0098	—	—	—
20	"	0.747	0.165	0.0097	0.0094	—	—	—
21	"	0.882	0.156	0.0121	0.0117	—	—	—
22	"	0.688	0.124	0.0094	0.0085	—	—	—
23	"	0.930	0.186	0.0124	0.0125	—	—	—
24	"	0.894	0.174	0.0120	0.0119	—	—	—
25	"	0.605	0.212	0.00655	0.0071	—	—	—
26	"	0.669	0.142	0.0088	0.0082	—	—	—
27	"	0.671	0.135	0.0089	0.0082	—	—	—
28	"	0.671	0.167	0.0084	0.0082	—	—	—

The eddy used in computing column No. 6 are 0.608 and 0.180 for standard and alloyed iron respectively.

*Results obtained by using reflecting instruments on two of above samples.

nection to the ballistic galvanometer and the other two for carrying the samples through the magnetic cycle.

Experience has shown that the method of testing using a step-by-step method as originally used by Ewing sometimes gives results that are not the same as those obtained on identical samples when tested by the wattmeter method. On the other hand ballistic measurements by the method employed usually show very close agreement with wattmeter tests. The ballistic tests made on the straight strips of both the one-lb. and 22-lb. samples were taken on the samples assembled with lapped joints and not with butt joints or in the open end testing coil which was used in the actual wattmeter testing.

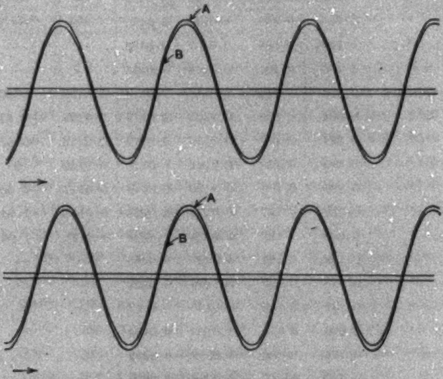

FIG. 7.—Apparatus for testing sheet iron.

22 lb. sample in test
Generator TH Form A18
A, wave of e.m.f. on magnetising winding
B, wave of induced e.m.f. in volt winding
Upper record, *B* in sample = 10,000
Lower record, *B* in sample = 15,000

Any generator that gives a sine wave under the small load used is suitable for testing the 22-lb. samples. The generator for the small set using the one-lb. samples is special because of the low frequency and low voltage employed.

The wave of e.m.f. used on the magnetizing windings of the large set and the wave of induced e.m.f. in the volt winding are shown in Fig. 7. It will be seen from inspection of the waves that the original wave of e.m.f. impressed on the magnetizing winding is satisfactory and that the apparatus is so constructed that there is no appreciable distortion in the flux wave in the sample under test. Form factor has been computed for the waves and shows them to be sinusoidal within the limits of error of the measures.

The inequality of distribution of flux along the large samples does not amount to more than 8 per cent.* The resulting error from this cause does not exceed a fraction of one per cent.

It may be of advantage to give results of some tests on rings made by the ballistic method and also by using wattmeters. These results show that under conditions that may be considered free from any errors due to assembling cut samples in various forms there is a good agreement between the results obtained by wattmeter separation and by ballistic measurements. Although this may not show anything very definite it shows that the results obtained in testing the cut samples are either correct or else that the ballistic determinations are affected to the same degree and in the same direction as the wattmeter measurements Table VI gives results in detail.

TABLE IV
APPARATUS FOR TESTING SHEET IRON
WATTS LOSS PER LB. IN 22 LB. EPSTEIN SAMPLES. 0.014 ALLOYED IRON
$B=15{,}000$

Sample No.	Total loss at 60 cycles	Eddy at 60 cycles	Hys. per cycle at 1 cycle per sec.
1	1.938	0.204	0.0289
2	1.969	0.265	0.0284

The requirements imposed on the wattmeter in testing on both sets are somewhat severe because of the low power factor. This is about 30 per cent at $B=10{,}000$ to 10 per cent at $B=15{,}000$ on the large set and 10 per cent on the small set. The reflecting dynamometers are constructed in such a way as to be free from any error due to low power factor, this point has been checked by testing them on an ironless reactance of carefully stranded conductor and the portable instruments of commercial type have been tested by comparison with the reflecting instruments and show no sensible error under the conditions of use.

These portable instruments are constructed to give full scale deflection with about 25 per cent power factor, and hence give a much larger deflection when used on this work than could be obtained on instruments built to meet the ordinary requirements of testing at high power factor.

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*From results communicated by A. B. Hendricks.

Before passing to a discussion of the results obtained with reference to the requirements first outlined table V will be referred to which is convenient for transforming results which are given in different terms to the same basis. By means of this table the results expressed in any of the usual terms may be readily converted into any other form. Such a table must of course include average eddy determinations as it has been the practice to sometimes state the result in hysteresis loss alone or to sometimes give total loss. Considering the fact that eddy loss is largely a function of the apparatus in which the iron is used and not wholly a function of the material; it is, unless separation tests are made on all samples, as accurate to convert test results from one form to another by this table as it is to give the results of total loss determination alone. The only reason that total loss determinations are of value in connection with any sort of testing apparatus is that the eddy loss is near enough constant so that the total loss is approximately a measure of the magnetic quality of the material. It must be borne in mind that close agreement between total loss measurements on any given apparatus does not mean that the accuracy is sufficiently good for practical

TABLE V

CONVERSION TABLE

FOR ALLOYED IRON SPECIFIC GRAVITY = 7.5. MULTIPLYING FACTORS FOR COMPARING RESULTS OF IRON TESTS QUOTED ON VARIOUS BASES

TO / FROM	Hys. watts per lb. per cycle at 1 cycle per sec. $B=5{,}000$	Hys. watts per lb. per cycle at 1 cycle per sec. $B=10{,}000$	Epstein total watts per kilo. 50 cycles $B=10{,}000$	Epstein total watts per lb. 60 cycles $B=10{,}000$	Hys. ergs. per cm. per cycle $B=10{,}000$	Hys. ergs. per gram per cycle $B=10{,}000$
Hys. watts per lb. per cycle at 1 cycle per sec. $B=5{,}000$		× 3.03	×333.3 + 0.275	×181.8 + 0.18	×500,980	×66,797
Hys. watts per lb. per cycle at 1 cycle per sec. $B=10{,}000$	×0.33		×110 +0.275	×60 +0.18	×165,340	×22,045
Epstein total watts per kilo. 50 cycles $B=10{,}000$	— 0.275 ×0.0030	— 0.275 × 0.00909		× 0.545 + 0.03	—0.275 ×1,504	— 0.275 ×200.5
Epstein total watts per lb. 60 cycles $B=10{,}000$	— 0.180 × 0.0055	— 0.180 × 0.0167	— 0.03 × 1.835		—0.180 ×2,756	— 0.180 ×367.5
Hys. ergs. per cm. per cycle $B=10{,}000$	× 1.996 $\times 10^{-6}$	× 6.045 $\times 10^{-6}$	×665 $\times 10^{-6}$ + 0.275	×363 $\times 10^{-6}$ + 0.180		×0.1333
Hys. ergs. per gram per cycle $B=10{,}000$	×14.97 $\times 10^{-6}$	×45.35 $\times 10^{-6}$	×4,988 $\times 10^{-6}$ + 0.275	×2,723 $\times 10^{-6}$ + 0.180	×7.5	

purposes unless the separated eddy for a given material is near enough to a constant value to make the hysteresis loss determined by subtraction very nearly that which would be obtained if actual separation was always made. These statements are made on the assumption it would not be permissible to consider any test as a test commercially possible which required several readings and a consequent separation by usual methods.

Some idea of the relation between the tests on individual samples and the general quality of the material under test can be obtained when it is stated that samples 1, 2, 3, 4 and 5 of table VI are from the same lot of material. The mean value of all of these samples is 1.27 and the difference between the highest and lowest is 0.008 or a variation of 3 per cent from the mean. Referring to table III there are also five samples from one lot of material, *vis.*, 7, 8, 9, 10, 11. The mean value of the measurements on these is 1.21 the variations between the highest and lowest 0.005 or about 2 per cent from the mean. Reference to table No. 1 shows five samples Nos. 11, 12, 13, 14 and 15, from one lot of material tested on a small set having a mean value of 1.18 a variation between extremes of 0.021 or 9 per cent from the mean. This variation is almost entirely caused by sample No. 11 but this could not be excluded and shows one disadvantage of the small sample, unless care is taken to distribute the punching throughout the material to be tested. It is believed that in this way just as accurate results can be obtained as with larger samples and they may be easily chosen from different parts of the lot of steel so as to obtain an accurate measure of this quality without completely destroying the sheets for the purpose for which they are to be used. The samples referred to in the tables were not chosen

TABLE VI

WATTS LOSS PER LB. IN 20 LB. RING SAMPLES 0.014" ALLOYED IRON $B = 10,000$

Sample No.	Total loss at 60 cycles	Eddy at 60 cycles	Hys. per cycle at 1 cycle per sec. by separation	Hys. per cycle at 1 cycle per sec. by ballistic	Per cent variation hys. by separation from ballistic
1	0.932	0.158	0.0120	0.0125	+3.20
2	0.943	0.193	0.0125	0.0126	—0.80
3	0.963	0.177	0.0131	0.0131	0.00
4	0.953	0.191	0.0127	0.0126	+0.80
5	0.922	0.184	0.0123	0.0121	+1.65

with any definite purpose of determining the quality of the material from which they were taken but were simply selected to get comparative tests by different methods.

All the samples were annealed after cutting and before testing. Of course the disadvantage of the small samples becomes very great if the testing of the samples must be done before annealing. As a workshop method there can be no advantage in testing without annealing, but for a standard method a sample should be chosen of dimensions such that the cutting does not change the quality by an appreciable amount. More recently it has become the part of certain requirements to give test results for $B=15{,}000$. Table IV shows results at this density on two samples with the total and separated loss measures. The advantages of the separate volt winding becomes quite apparent at this density also reference to Fig. 3 will show that the small set is not applicable to testing at this density. The details of the separation tests that were made on the various samples will not be given further than to state that on the small set 10, 13, 16 and 19 cycles were used and on the 22-lb. samples 25, 30, 40, 50 and 60 cycles were used. It is believed that separation at two extreme cycles is satisfactory but in this particular work it was felt that some degree of precision was added by making observations at two or three intermediate frequencies.

In giving results of tests made by the two arrangements which have been described it is not possible to include more than a small part of the total number of samples that have been tested. It may be well to call attention to this point before passing to the conclusions as it will no doubt be impossible to exclude from consideration results that are not referred to in the tables. The tables therefore should be accepted as a general indication of the results obtained rather than representing sufficient data from which conclusive averages may be derived. In no case have conclusions affecting the procedure to be followed in the work been reached on a basis of less than 100 samples tested and usually many times this number have been considered.

The accuracy that can be obtained in testing the one-lb. samples should be considered as subject to a possible variation of 5 per cent from the actual hysteresis loss in any given sample. As the eddy loss in testing this form of sample has no direct connection with the eddy loss that would occur in completed apparatus, statement of total loss determinations in the open end testing coil cannot be considered. The apparatus which tests the Epstein samples will give total loss within about 2 per cent of the true value and hysteresis loss without separation usually within somewhat closer limits than figures given for the small set. Due to the fact that the eddy loss found in testing the Epstein samples represents very nearly that which is found in ordinary transformers, total loss determinations on the 22-lb. samples have some value without deducting the eddy. On the whole the accuracy with this arrangement must be considered superior to that obtained in the open end testing coil.

The accuracy obtainable with either arrangement is believed to be well within the limits of the ability of the producers of sheets to secure uniformity of product and of designers to produce definite results with material of uniform and known quality. We are speaking now of the errors in testing individual samples and of course in speaking of material and apparatus we must use the same terms and consider that single sheets of material and individual transformers, for instance, are referred to. We may then consider that the accuracy with either method is satisfactory and take up the other requirements which were referred to in the beginning of the paper.

The accuracy of sampling with the 22-lb. sample is within 3 or 4 per cent for fairly uniform material. The accuracy of sampling with the one-lb. samples may give errors as much as 10 per cent but this can be reduced by careful attention in choosing the samples. It is more difficult to reach a definite conclusion on this point than on any other and to support any opinion by properly arrayed facts. It would seem fair to state that five of the small samples may be so chosen as to give a result as good as could be obtained with one of the 22-lb. samples and destroy less material for the test.

With reference to the third requirement it should be possible to directly compare results obtained by different methods without the necessity of recourse to ballistic galvanometer tests. On account of the extensive use that has already been made of Epstein apparatus it would seem that not much argument is required to show that the 50- by 3-cm. sample should be chosen as the standard size and that any standard method of measurement should be based on testing a sample of this dimension either 22-lb. at once or in several parts. In this way all considerations of the preparation of the material can be made general and will affect all the tests alike. While the method of measurement which uses the open end testing coil has not been employed commercially to test the samples of larger dimensions, it has been shown experimentally that it would be equally satisfactory in operation using a definite portion of the complete 22-lb. sample.

With reference to the fourth requirement it is difficult to give estimates of the cost of testing by the various methods which have been proposed. It is believed that including the cost of material the expense per sample tested would be at least 10 to 20 times with the modified Epstein arrangement what it would be with the small set. On the other hand the successful employment of the small set so far requires the use of a steady pier and instruments which are not to be considered as ordinarily suited to workshop requirements. As a final conclusion it is felt that the small set is eminently suited to such situations as require a very large number of tests where the cost of the labor and material in testing is important. Such situations would usually permit of the employment of at least one man with the necessary degree of intelligence and experience to keep the accuracy of the results within required limits.

For situations where the total number of tests to be made is not sufficient to maintain a permanent organization for the work the Epstein arrangement is most satisfactory and it is believed that the form described is in some respects superior to the original arrangement. The amount of material required is somewhat large but the results obtainable are accurate enough to leave nothing desired from this point of view. The whole equipment is strong and can be operated by any one of ordinary intelligence and without special training. Because this method possesses the above desirable features to a marked degree it should become ultimately the universally accepted standard method of testing.

It would not be proper to leave the subject without referring briefly to the method of testing which has already been cited in the reference on the first page of this paper and which was developed by the National Bureau of Standards. The accuracy obtainable by this method is undoubtedly superior to that of any previously described and the method therefore marks a distinct advance in the art. The increase in accuracy over previous methods similar to those described is not sufficient to be of importance in practical work. The use of this apparatus it is believed will be found chiefly in connection with accurate research work on relatively small samples of material. The added accuracy is obtained at the expense of increased length of time required to assemble and test the samples.

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THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL

BY MALCOLM MAC LAREN

In the experiments described below, investigations were made upon the variation in hysteresis loss in sheet steel when passing from ordinary atmospheric temperatures up to the point at which the material becomes non-magnetic. The measurements were made over as wide a range of induction as possible. In order to get consistent results it was found to be important that the observations at each temperature be made quickly, partly on account of the difficulty of holding the temperature constant and partly because, even with constant temperature slow changes occurred in the hysteresis which become especially pronounced at the higher temperatures.

Method of Measurement. The method of measurement which was employed was a modified form of the well known two-frequency method in which alternating current is applied to the test sample and the combined hysteresis and eddy current loss is measured. The hysteresis loss $=a f B^x$ and the eddy current loss $=\beta f^2 B^2$, where a and β are constants, f is the frequency in cycles per second, B is the induction per square centimeter, and x is an unknown quantity equal to approximately 1.6.

If w_1 = the measured loss at a frequency f_1 and w_2 = the measured loss at a frequency f_2 then

$$w_1 = a f_1 B^x + \beta f_1^2 B^2$$

and

$$w_2 = a f_2 B^x + \beta f_2^2 B^2$$

Solving these equations for β at any induction B we get:

$$\beta = \frac{w_1 f_2 - w_2 f_1}{B^2 (f_2 f_1^2 - f_1 f_2^2)}$$

Knowing β, the eddy current loss can be determined and by subtracting this from the measured loss the hysteresis can be obtained. In making the measurements it is desirable to use a low frequency for the lower limit as then the measured loss is principally hysteresis. The higher frequency should be considerably above the lower in order that errors in observations should not introduce too great an error in the determination of β. In all these experiments 25 and 60 cycles were the two frequencies used.

If measurements had been made upon the sample through a single exciting coil a correction would have been necessary on account of the $I^2 R$ loss in this coil. This is difficult to make accurately with varying temperature and has been avoided in this case by placing a primary and secondary winding upon each sample.* If the current coil of the wattmeter is connected into the primary and the potential coil across the secondary, then the combined hysteresis and eddy current loss will equal the wattmeter reading multiplied by the ratio of the primary to the secondary turns. The corresponding induction is found from the formula:

$$B = \frac{V \times 10^8}{\sqrt{2} \times \pi \times A \times f \times S}$$

where V = secondary voltage.
A = cross section of sample in square centimeters.
S = number of secondary turns.

The arrangements of connections is shown in Fig. 1. The ammeter in the primary circuit was not required in determining the hysteresis loss but was useful in following the change in magnetizing current as the material approached saturation. Instruments were used which contained no iron in their magnetic circuits and were, therefore, not affected by a change of frequency. The wattmeter was calibrated for low power-factor and was compensated for the loss in its potential coil. It was necessary, however, to correct for the loss due to the voltmeter current. This was done by observing the difference in the wattmeter readings with the voltmeter circuit closed and open at constant voltage. A number of such readings were taken from which a curve was plotted showing the voltmeter loss for any voltage over the range covered by the experiments.

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The alternator used during the test gave an e.m.f. wave of approximately sine form and was of sufficient capacity to have its field practically unaffected by the maximum armature current of 2.5 amperes required for the test sample. Distortion of the wave form was further minimized by connecting the primary winding directly across the terminals of the alternator and varying the voltage applied to the sample by varying the field excitation. The alternator was direct coupled to an interpole shunt-wound motor in which the speed could be varied from 750 to 1800 rev. per min. by varying the field excitation. These limits corresponded to 25 and 60 cycles at the alternator. A magneto speed indicator, direct coupled to the motor generator set, allowed the frequency to be determined instantly, and permitted the change from one test frequency to the other to be made very quickly. A storage battery was used for supplying power to the motor, so that the voltage and frequency at the sample remained very steady while the observations were being made.

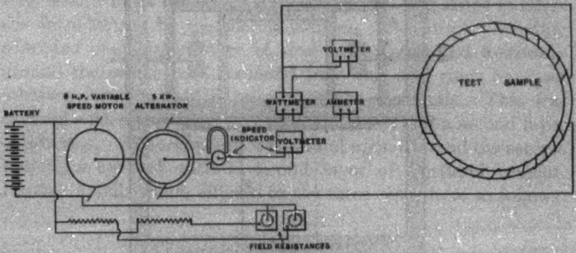

FIG. 1

This method of measurement was checked by comparing results with direct measurements of the hysteresis loop for several inductions in the manner described below.

The temperature was determined by platinum-iridium thermocouples and a potentiometer. As a check two couples were used in each experiment and were placed in opposite sides of the sample. Differences of temperature of one degree could be noted with these couples.

Electric Furnace. The furnace used for heating the sample is shown in section in Fig. 2. The inside heater *A* consisted of a corrugated porcelain dish with "nicrome" heating wire wound in the corrugations. The outside heater *B* was made up of a sheet steel cylinder insulated with a thin layer of asbestos, about this were wound fifteen turns of "nicrome" wire; strips of asbestos were placed between turns and the whole was covered with a thick layer of asbestos. Alternating current was used for the heater and the temperature was controlled through regulating transformers. The sample *S* was heated uniformly by placing it in the center of the heating chamber. This chamber was closed at the top by a fire clay disk *C* which rested upon the top of the inside heater and fitted closely against the inside surface of the outside heater. An intermediate chamber was formed by placing the heaters in a fire clay pot *D* and closing the top with a disk of thick asbestos and a fire clay cover *E*. The outside of the furnace was covered with asbestos. All joints were sealed with clay. Small holes were cut in the sides of the retaining vessel and in the outside heater to allow the entrance of the thermo-couples *T* and these holes were sealed with asbestos.

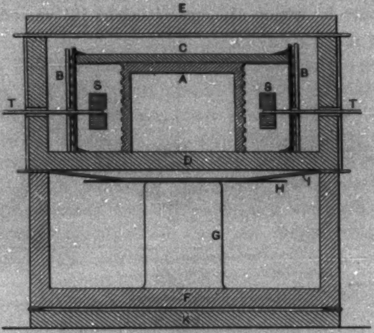

FIG. 2

The flow of heat through the bottom of the furnace was checked by mounting this upon a second fire clay pot *F* in which thermal currents were broken up by means of a glass dish *G*, a glass plate *H* and an asbestos disk *I*. The furnace was further insulated from the floor by a fire clay disk *K*.

The maximum power taken by the furnace during the experiments was 1500 watts. This gave an average temperature rise of about 100 deg. cent. per hour.

Test Samples. Measurements were made upon three samples. The same material was used in samples No. 1 and No. 2 and corresponded to a good grade of commercial armature steel. The average thickness of the plates was 0.43 mm. The essential difference between these samples was that in No. 2 the eddy currents which might exist between plates was checked by placing very thin strips of mica between every second plate. Sample No. 3 was made up of high silicon transformer steel the average thickness of plate being 0.349 mm. In each case the rings were 2.54 cm. wide and had a mean diameter of 27.9 cm. They were separated at the center by U-shaped spacing strips to allow the introduction of the thermo-couples. The primary winding consisted of a single layer of iron wire distributed uniformly around the sample and insulated from the steel rings by sheet asbestos reinforced with mica near the terminals. This was covered with a thin layer of Portland cement and a second layer of asbestos. The secondary was wound upon this and the sample was then covered with a second layer of Portland cement. Further details which differed in the three cases were as follows:

	Cross section	Primary turns	Sec. turns	Weight
Sample No. 1	14.0 sq. cm.	195	166	9.6 kg.
" No. 2	12.9 "	144	156	8.874 "
" No. 3	13.27 "	154	161	8.611 "

Results. In each case observations were taken at several temperatures first at 25 cycles, then at 60 cycles and then a few check readings were again made at 25 cycles to see that the losses had not changed while the measurements were being made. The results were then plotted in the form of curves between loss per kilogram and induction, the observed points being indicated in each case. From these curves β, the coefficient of the eddy current loss, was first determined and from this the eddy current loss was separated from the hysteresis for 25 cycles at several different inductions. Finally curves were derived which showed the change in hysteresis loss with the temperature at constant induction.

Sample No. 1. After the test had been started on this sample and the temperature had reached about 150 deg., measurements indicated that a short circuit was developing in the windings. The test had to be discontinued, but the temperature was raised to about 400 deg. in the hope of removing the defect. Later measurements after the cooling showed that the short circuit had disappeared and the test was continued up to the non-magnetic point. It was found, however, that above 500 deg. the losses increased with rise of temperature which was probably due to a reappearance of the short circuit, so that the measurements above this point are not of great value except as they serve to check the results obtained on sample No. 2. Table I shows the value of β and the corresponding values of eddy current and hysteresis loss at 25 cycles for this series of observations. The average value of β for each temperature has been used in the determination of the eddy current loss except for the highest temperatures where this does not seem permissible.

It might seem that variations of 15 or 20 per cent in the values of β which occur in the test would indicate correspondingly large errors in the observations and give very inaccurate results in the determination of the hysteresis loss. It should be remembered, however, that $\beta = \dfrac{w_1 f_2 - w_2 f_1}{B^2 (f_2 f_1^2 - f_1 f_2^2)}$ in which the measured losses affect the numerator only.

Taking one of the worst cases, which occurs in the measurements at 282 deg. for B equal 10,000, when the value of β is about 20 per cent less than the average, the measurements showed that $w_1 = 2.94$ and $w_2 = 1.05$ and the numerator in the above was therefore $2.94 \times 25 - 1.05 \times 60 = 10.5$. In order that the observed value of β should equal the average this figure should be increased to 13 and this difference would be accounted for by an error of about 3 per cent in the value of w_1 or about 4 per cent in the value of w_2 . . It will also be seen from the table that at this point the eddy current loss equals 0.155 watt per kg. out of a total measured loss of 1.05 watts per kg. This means that even with an error of 20 per cent in the determination of the eddy current loss the error introduced in the value of the hysteresis loss would only amount to 4 per cent.

Fig. 3 was plotted from the values for the hysteresis loss given in the table. The break in the curves between 150 and 200 is accounted for the fact that the test was not continuous.

TABLE I

	24 deg. cent.			140 deg. cent.			197 deg. cent.		
B	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
14000	0.0456	0.61	2.24	0.0284	0.41	2.20	0.0291	0.384	1.90
12000	0.0462	0.45	1.57	0.0345	0.301	1.53	0.0305	0.284	1.37
10000	0.0510	0.312	1.06	0.0330	0.218	1.05	0.0306	0.196	0.944
8000	0.0515	0.200	0.72	0.0350	0.134	0.716	0.0315	0.126	0.615
6000	0.0550	0.112	0.448	0.0365	0.075	0.445	0.0355	0.071	0.367
Average..	0.0499			0.0335			0.0315		

282 deg. cent.			390 deg. cent.			460 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0290	0.304	1.71	0.0256	0.325	1.32	0.0319	0.385	1.05
0.0218	0.223	1.28	0.0245	0.240	1.01	0.0294	0.285	0.825
0.0200	0.155	0.895	0.0243	0.166	0.718	0.0267	0.197	0.603
0.0244	0.099	0.581	0.0256	0.107	0.466	0.300	0.126	0.394
0.0291	0.056	0.344	0.0333	0.060	0.268	0.0350	0.071	0.219
Av.0.0248			0.0266			0.0316		

535 deg. cent.			600 deg. cent.			665 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0410	0.481	0.829	0.0613	0.690	0.655			
0.0390	0.354	0.668	0.0595	0.510	0.525			
0.0360	0.246	0.492	0.0552	0.352	0.398	0.147	0.92	0.19
0.0370	0.157	0.323	0.0501	0.225	0.265	0.132	0.53	0.17
0.0435	0.089	0.161	0.0549	0.127	0.134	0.121	0.27	0.098
Av. 0.0393			0.0562					

708 deg. cent.			749 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
—	—	—	—	—	—
—	—	—	—	—	—
0.147	0.92	0.105	—	—	—
0.133	0.53	0.130	0.216	0.86	—0.15
0.121	0.27	0.083	0.179	0.40	—0.04

Sample No. 2. Fewer primary turns were used in this case than with sample No. 1 in order to get greater clearance between turns and more care was taken with the insulation, as a result there was no indication of any failure of insulation during the test upon this sample. The measured losses in this case, which are representative of the three sets of measurements, are shown in Figs. 4 and 5, the value of β and the corresponding eddy current and hysteresis losses are given in Table II and the values of the hysteresis loss shown in the table are plotted with reference to temperature in Fig. 6.

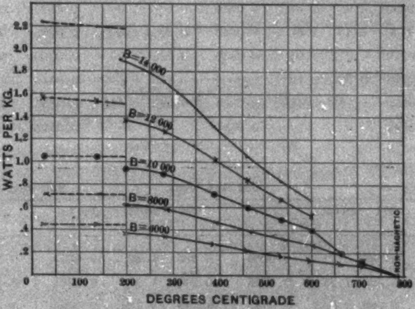

FIG. 3

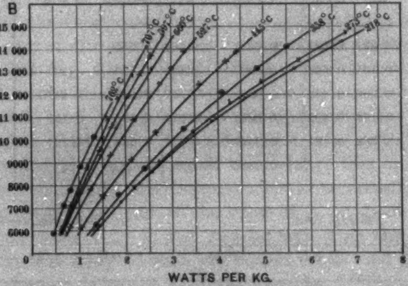

FIG. 4

Comparing Figs. 3 and 6 it will be seen that the two samples show the same general characteristics. They both show a remarkably small change in loss at the lower temperatures; they also both show a sudden drop in the curves although this occurs at about 100 deg. higher temperature on sample No. 2 than on sample No. 1. Perhaps too much reliance should not be placed upon the results obtained with sample No. 1 on account of its defective insulation but it is suggestive to note that from 200 to 400 deg. the rate of heating in No. 1 was 80 deg. per hour and in No. 2 it was 35 deg. per hour and this might be a possible explanation of the differences which occur in the two samples over this range of temperature.

TABLE II

	218 deg. cent.			273 deg. cent.			358 deg. cent.		
B	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
14000	0.0342	0.421	1.66	0.0342	0.407	1.55	0.0259	0.320	1.49
12000	0.0341	0.310	1.23	0.0328	0.299	1.19	0.0242	0.235	1.16
10000	0.0348	0.216	0.884	0.0318	0.207	0.869	0.0256	0.164	0.866
8000	0.0345	0.138	0.582	0.0340	0.133	0.597	0.0274	0.105	0.595
6000	0.0351	0.077	0.375	0.0337	0.075	0.377	0.0275	0.059	0.371
Average	0.0345			0.0332			0.0261		

445 deg. cent.			527 deg. cent.			597 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0240	0.277	1.16	0.0208	0.265	0.765	0.0190	0.251	0.519
0.0226	0.203	0.937	0.0203	0.195	0.625	0.0192	0.185	0.435
0.0220	0.141	0.699	0.0223	0.135	0.465	0.0191	0.128	0.347
0.0218	0.091	0.479	0.0222	0.087	0.318	0.0192	0.084	0.246
0.0225	0.051	0.299	0.0230	0.049	0.191	0.0245	0.046	0.135
Av. 0.0226			0.0217			0.0205		

660 deg. cent.			707 deg. cent.			762 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0270	0.361	0.354	0.0250	0.335	0.253	—	—	—
0.0282	0.265	0.285	0.0248	0.246	0.234	—	—	—
0.0292	0.184	0.244	0.0256	0.171	0.197	0.0357	0.223	0.002
0.0308	0.118	0.172	0.0260	0.109	0.149	0.0360	0.144	0.009
0.0323	0.066	0.099	0.0346	0.061	0.084	0.0364	0.082	-0.001
Av. 0.0295			0.0273					

It is possible that sufficient refinement was not entered into in these measurements to enable an accurate determination to be made of the exponent x in the expression, hysteresis loss $w = a\,f\,B^x$; but the results are so consistent among themselves and check so well with the direct measurement of the hysteresis loops, that comparative values at different temperatures should be fairly correct. Transforming the above expression into the logarithmic form,

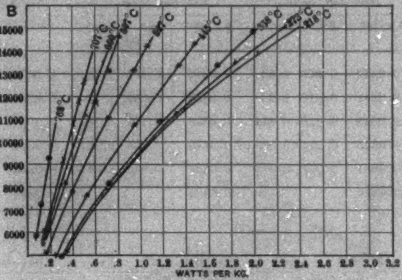

FIG. 5

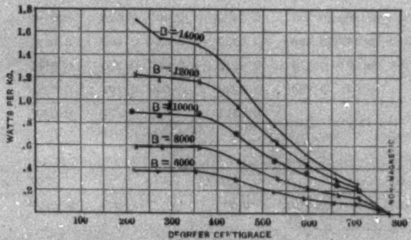

FIG. 6

$$x = \frac{\log w - \log (a\,f)}{\log B}$$

a preliminary investigation showed that x was practically constant so that at each temperature this was assumed equal to

1.6 at the minimum induction and a value was obtained for the constant log $(a f)$ which changes only with the temperature. The value of x at the higher inductions was then obtained by using the values of w given in table II. The results are shown below and indicate that the law governing the change of hysteresis loss with the induction is unaffected by the temperature even near the non-magnetic point.

B	218 deg. cent.	237 deg. cent.	358 deg. cent.	445 deg. cent.	527 deg. cent.	597 deg. cent.	660 deg. cent.	707 deg. cent.
6000	1.600	1.600	1.600	1.600	1.600	1.600	1.600	1.600
8000	1.598	1.600	1.601	1.601	1.605	1.615	1.610	1.160
10000	1.604	1.602	1.602	1.603	1.608	1.606	1.609	1.604
12000	1.608	1.604	1.603	1.603	1.608	1.606	1.594	1.591
14000	1.614	1.606	1.604	1.600	1.603	1.600	1.591	1.570

Sample No. 3. The results of the test upon this sample are shown in table III, and the variation of the hysteresis loss with the temperature is shown in Fig. 7.

TABLE III

	47 deg. cent.			300 deg. cent.			402 deg. cent.		
B	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.
14000	0.0097	0.109	0.991	0.0113	0.137	0.756	—	—	—
12000	0.0090	0.080	0.782	0.0114	0.101	0.612	0.0093	0.085	0.515
10000	0.0080	0.056	0.576	0.0107	0.069	0.471	0.0092	0.059	0.402
8000	0.0089	0.035	0.386	0.0113	0.045	0.325	0.0101	0.038	0.289
Average	0.0089			0.0112			0.0095		

	508 deg. cent.			597 deg. cent.			659 deg. cent.			700 deg. cent.		
B	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.
14000	—	—	—	—	—	—	—	—	—	—	—	—
12000	0.00804	0.076	0.373	0.0109	0.107	0.154	0.0120	0.108	0.083	—	—	—
10000	0.00865	0.053	0.313	0.0118	0.074	0.138	0.0133	0.083	0.064	0.0160	0.100	0.010
8000	0.00878	0.034	0.248	0.0129	0.048	0.117	0.0142	0.057	0.057	0.0175	0.070	0.011
Average	0.00849			0.0119								

The values of *x* determined in the same manner as for sample No. 2 were as follows:

B	47 deg. cent.	300 deg. cent.	402 deg. cent.	508 deg. cent.	597 deg. cent.	659 deg. cent.
8000	1.600	1.600	1.600	1.600	1.600	1.600
10000	1.604	1.602	1.597	1.586	1.574	1.574
12000	1.605	1.598	1.585	1.569	1.560	1.570
14000	1.606	1.596	——	——	——	——

An investigation was also made upon the permeability of this sample as it approached and came out of the non-magnetic state. This was done by keeping a constant magnetizing current of 2.5 amperes 60 cycles in the primary and noting the change of induction as determined from the secondary voltage as the temperature changed. The results were as follows:

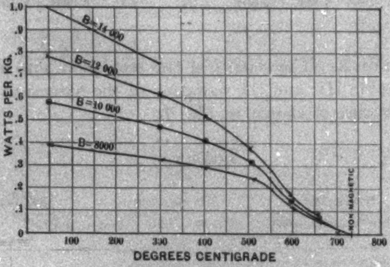

FIG. 7

Heating		Cooling	
Induction	Temperature	Induction	Temperature
8200	702 deg. cent.	8280	707 deg.cent.
7460	715	7660	715
6010	727	6015	726
4660	732	4710	729
3550	735	3360	732
1610	737	1530	735
916	737	765	737
0	737	0	737

Direct Measurement of Hysteresis. As a check upon the above results, hysteresis loops were plotted at several inductions upon sample No. 2. The arrangement of the apparatus in this test is shown in Fig. 8.

The magnetizing force in the sample was determined from the expression $H=\frac{2\,S\,i}{10\,r}$ where S is the number of primary turns, i is the current in amperes and r is the mean radius of the test ring. For sample No. 2, $H=2.06\ i$. i was measured by the ammeter A in the primary circuit. Four German silver resistance frames with sliding contacts were used for varying the magnetizing current. A d'Arsonval galvanometer G was placed across the terminals of the secondary. A shunt was used with the galvanometer in order to keep the deflections within a suitable range and reduce the time of the cycle.

If a magnetizing force H is applied to the sample and is gradually reduced to zero by reducing the current at such a rate as to keep a fairly constant deflection on the galvanometer and if the magnetizing current is then reversed and gradually increased until $-H$ is reached, then the average galvanometer deflection multiplied by the time required for the reversal is a measure of the total change of induction in the sample in passing from $+\mathrm{H}$ to $-H$. In these tests simultaneous readings upon the ammeter and the galvanometer were taken at 10-second intervals. If the galvanometer deflection varied, the average during the interval was recorded. In this case the sum of the galvanometer readings multiplied by 10 was the measure of the change of induction. The galvanometer was calibrated by means of a potentiometer and a standard cell, and one division of the galvanometer scale was found to equal 2.74×10^{-4} volt, so that the total change of induction equals

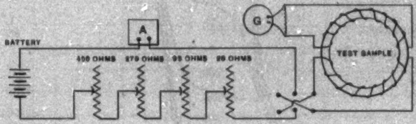

FIG. 8

$$\frac{2.74\times10^{5}\times\text{sum of deflections}}{\text{number of secondary turns}}$$

and the induction per square centimeter in the sample corresponding to H was therefore:

$$B=\frac{2.74\times10^5\times\text{sum of deflections}}{2\times12.9\times156}=67.8\times\text{sum of deflections}.$$

It also will be readily seen that the change in induction due to the change in the magnetizing force between consecutive readings $=2\times67.8\times$galvanometer reading.

The method of plotting the hysteresis loop from a set of readings between $+H$ and $-H$ is then to take the sum of the galvanometer readings between these limits to determine B corresponding to the maximum positive value of H. At the end of the first 10 seconds the ammeter reading will show a magnetizing force H_1 and the galvanometer reading will give the corresponding change in induction B_1. The actual induction in the sample due to H_1 will then equal $B-B_1$. Other points on the hysteresis loop will be found in the same way until $-B$ corresponding to the maximum negative value of H is reached. As a check upon the accuracy of the observations it is well to continue the test until the starting point is again reached, the sum of the positive galvanometer deflections should then be equal to the sum of the negative deflections.

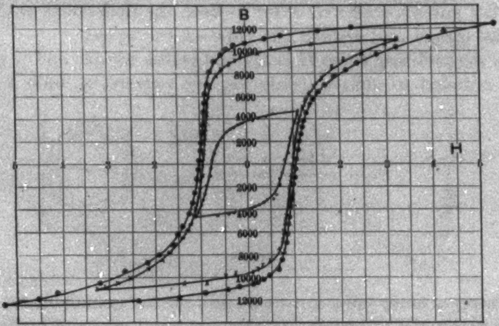

FIG. 9

It should be noted that this method of measuring hysteresis loops possesses a considerable advantage over the usual step by step method with a ballistic galvanometer, in the fact that it is not necessary to predetermine the resistance steps as this is taken care of entirely by watching the galvanometer deflection. As far as the writer is aware this method has not previously been applied to small samples requiring laboratory instruments for the measurements. It was first suggested by Mr. C. F. Scott and developed by Mr. Scott and the writer for the purpose of determining the permeability of the nickel-steel field ring of the first large generator installed at Niagara Falls. The field ring itself was the test sample in that case and the magnetic flux was of such a magnitude that a voltmeter could be employed in the secondary circuit for the measurement of the induction.

Three hysteresis loops obtained by this method are shown in Fig. 9. Immediately after these were taken, measurements were made by the two-frequency method, and the values of the watts lost per kg. at 25 cycles determined by the two methods were as follows:

	Loss by direct measurement	Loss by two-frequency method
For B— 4650....................	0.306	0.282
" B—11000....................	1.16	1.22
" B—12400....................	1.595	1.55

The writer is indebted to Mr. Philander Norton for his valuable assistance in making the observations and in calculating results.

DISCUSSION ON "EFFECT OF TEMPERATURE ON THE HYSTERESIS LOSS ON SHEET STEEL", "COMMERCIAL TESTING OF SHEET IRON FOR HYSTERESIS", NEW YORK, APRIL 14, 1911.

C. H. Sharp: It may not be amiss to consider very briefly some of the improvements in method and apparatus for magnetic testing and also some of the difficulties which are met with in this class of work.

Testing by the ballistic galvanometer method has been greatly simplified by the use of a long period D'Arsonval galvanometer as ballistic instrument in place of the old undamped moving needle galvanometer which made such a record for itself as a troublesome and time-wasting instrument. The D'Arsonval galvanometer is given any required degree of damping so that it may be used without a loss of time in bringing it to rest. It is calibrated by reference to a standard of mutual induction and its constant is expressed no longer as a ballistic constant, but rather in terms of line of force cut per centimeter throw. The long period is required not so much to enable the throws to be read with accuracy as to obviate the effects of magnetic viscosity in the specimen.

The errors involved in the use of yokes in testing straight specimens have been taken account of and yokes with compensating windings which carry sufficient current to overcome the magnetic reluctance of the yokes, joints, etc., have been devised and put into practical use.

The Picou permeameter, an instrument designed on this principle, has been found in our work to have a very limited range of usefulness and not to be a successful practical instrument. The investigations of the Bureau of Standards along these lines have been most thorough and painstaking and have resulted in the development at the Bureau of Standards of practical forms of compensated yokes wherewith really accurate permeability and hysteresis tests can be made with a reasonable expenditure of time.

Among instruments intended for giving a relatively quick determination of permeability curves and hysteresis loops, by substituting a more convenient device in place of the ballistic galvanometer, the Koepsel instrument has probably a predominate place. The compensation of the yoke reluctance in this instrument, however, is very imperfect and the results obtained for it require so much correction to take account of the unknown reluctance of the yoke, and of the joints, that it can hardly be considered as giving very accurate results in any work except in the comparison of samples of similar material.

Practically, not only the hysteresis loss but also the eddy current loss should be known. This fact leads directly to the wattmeter method of testing samples. If the iron is tested at the same induction with two different frequencies of the alternating current or if it is tested with the same frequency but at two different values of the induction, the eddy current and hysteresis losses can be separated from each other. There is no practical difficulty in measuring the losses in even quite a small sample of iron if the proper instruments are available. The wattmeter used must be one which is accurate on low power factors. If the sample is quite a small one, some special sensitive wattmeter is required such as for instance, the suspended type, using a mirror and spot of light for reading. It is advisable to use a separate winding for the potential measurements as Professor MacLaren has done. Sometimes a third winding is put on which is connected to an electrostatic voltmeter. Under these conditions the electrostatic voltmeter indicates the total e.m.f. set up in the winding, and consequently the maximum induction; that is no correction is necessary for fall of potential in the windings, due to the voltmeter current. The temperature of the windings and of the sample should be accurately controlled and the temperature at which the losses are measured should be stated. This is very seldom done, but in as much as the eddy current loss must have the same temperature coefficient as the resistance temperature coefficient of the iron; namely about 0.5 per cent per degree, the necessity for stating the temperature is obvious. Inasmuch as the sample may tend to rise considerably in temperature during a test, it has been found in our work advisable, at any rate when working with small samples, to immerse the entire arrangement in an oil bath. Furthermore, if the temperature of the oil bath is kept at some definite value, as for instance 50 deg. cent. the losses are measured at a temperature comparable with the temperature which the iron will actually have in use. It would be advisable therefore that a standard temperature at which these tests are to be made should be agreed upon.

The test should be made with a sine wave form. This is required because the losses vary with the wave form. It is not sufficient simply to assume from the fact that the wave form of the generator is practically sinsuoidal, that the form factor, which enters directly into the computation of the maximum induction produced in the iron, is exactly 1.11. The actual form factor of the wave of e.m.f. set up in the iron should be investigated and its actual value determined. Any error in the determination of the form factor affects the value computed for the maximum induction by the same percentage, and consequently affects the value for the losses at a given induction by a considerably larger percentage. The form factor may be determined either from an actual plot of the wave, or by rectifying the wave by means of a commutator attached to the shaft of a synchronous motor, and comparing the value of the rectified e.m.f. as indicated by a permanent magnet voltmeter with the value of the alternating e.m.f. as measured by a dynamometer type of voltmeter containing no iron. In this arrangement it is not always easy to be sure of perfect contact between the commutator and the brush, so that a good deal of care needs to be used, to avoid error from this cause.

The pieces from which the magnetic circuit is built up need to be carefully insulated from each other. The exact method of building a magnetic circuit does not seem to be a matter of great importance. In the Bureaus of Standards apparatus the joints at the corners of the magnetic square are more perfect than in the Epstein apparatus so commonly used in Germany. The result of this is that the wattmeter is used at a better power factor. In the Möllinger apparatus the samples are continuous, ring-shaped stampings and the windings are quickly put on by a special arrangement. This gives a more perfect magnetic circuit than either of the other forms, but requires a less economical form of stamping and gives practically the same results as the Epstein apparatus. Wild, in a recent paper before the Institution of Electrical Engineers, reported finding several per cent higher loss in the Bureau of Standards' style of magnetic square than in the Epstein style. He attributes this to the increased hysteresis in the corner pieces due to bending, and considers the results of the Epstein apparatus to represent more nearly the true values.

The question of the sample seems to be the most difficult one in connection with the wattmeter method of testing. In the Epstein apparatus 10 kilograms of iron are used. The quantity is so considerable and the individual pieces are of such size that the resultant sample can scarcely fail with proper selection, to be representative of the iron. Where smaller samples are used, the doubt increases as to the representative quality of the sample, and this seems to be the chief difficulty in the use of small samples for the wattmeter test.

Mr. Robinson's method presents the wattmeter test reduced to the greatest possible simplicity. The only question about it seems to be that of the size of the sample and in as much as Mr. Robinson has found it to give satisfactory results in the immense amount of work which he has done with it, and the results of which have been of the very greatest commercial importance, it is hardly open to doubt that as a workshop method his is a most excellent one.

Edwin F. Northrup: I have been interested in Professor MacLaren's paper on methods of hysteresis testing because of the importance of the subject, and also, for what the paper tells and suggests.

While I do not feel as competent to discuss methods of iron measurement as I would methods of electrical measurement, nevertheless I have some thoughts regarding the subject of the paper which may be worth expressing.

In addition to the losses in a transmission system which result from depreciation of the equipment there are two sources of loss which have received a searching study, namely, the copper losses on the line and the iron losses in the generators and transformers. The control of the copper losses has become so good that it is not unreasonable to specify conductivities for the copper, or aluminum conductors, used to within a fraction of a per cent, and conductivity measurements can be made by a single observer with great rapidity to within a quarter of one per cent. Yet, without data at hand to confirm the suggestion, I should suppose that it is costing thousands of dollars to overcome unnecessary hysteresis losses, to hundreds of dollars spent in overcoming unnecessary copper losses. Severe specifications respecting the quality of conductor materials, in the present state of engineering development, can be made with much better justification than they can respecting the qualities of transformer irons and steels. This is in part due to the fact that conductivity measurements are so much more easily and precisely made than iron measurements. Any contribution, therefore, to our knowledge of practical methods for making iron measurements is welcome.

Iron measurements have directly in view a commercial end and in devising methods for making measurements one should work from the commercial view point. Laboratory precision, as applied to many electrical measurements, is of relatively small importance in making iron measurements as compared with simplicity, rapidity and the use of few observers.

Professor MacLaren presents us with two methods of testing iron, and with the first of these methods he obtains results which are very interesting. His first method, the wattmeter method is not new but his second method, the direct measurement of hysteresis, is, as far as I know, described in print for the first time. I have had the opportunity of examining the construction of his samples, the apparatus used in his tests, and myself have made a trial of his second method. I am convinced that his work was done with painstaking care and that all his statements are conservative. His construction of a furnace for regulating the temperature of the samples, I think is particularly well adapted to what it has to do.

The curves, giving the relation, between watts lost per kilogram of steel, and degrees centigrade, are interesting in the extreme. It would appear from these curves that a reduction in the hysteresis loss to one fourth its original value, by an elevation of temperature of some 500 deg., is a physical fact and one of much significance. It looks as if the molecules turn about under the directive force of the magnetic field with less friction as they become further separated by elevation of temperature. One should also expect considerable diminution in the eddy-current losses, with elevation of temperature, from the increase in the specific resistance of the iron. Referring to tables I, II, III, of the article we find this not to be true throughout the entire ranges of temperature used. In table I, for any given induction, say 10,000, we have the eddy-current loss, starting at 24 deg.

equal to 0.312 and falling at 390 deg. to 0.166, but then rising again at 535 deg. to 0.246 and continuing to rise at 708 deg. to 0.92. Sample No. 1 was thought to be defective in insulation, but there is no regular decrease beyond 597 deg. even in sample No. II, table II. If both the hysteresis loss and the eddy-current loss in transformers decidedly decreases with elevation of temperature, and if the decrease in loss should prove to exceed the increase in copper losses, and if the elevated temperature does not gradually diminish with time the permeability of the steel, it might actually result that transformers would show a total higher efficiency when run hot than when run cold. It is doubtful if experiment would justify this conclusion, but I suggest it as a research for some one, to make a prolonged test of the relative efficiencies of properly insulated transformers operated at, say 40 deg. temperature and 200 deg. temperature. It is not improbable that the insulation problem could be cared for with asbestos covered wire and some of the new insulating compounds.

The data at the bottom of page 548, in which Professor MacLaren finds that the curves, showing change in induction as the iron passes through the magnetic point, practically overlap, both for an increasing temperature and for a decreasing temperature, have, to my mind, an important physical significance. On many samples of steel tested by me, to determine their heating and cooling curves, I found that in all cases the recalescent point lay some 26 deg. or more below the decalescent point. In one low carbon steel the decalescent point was at 724.4 deg. C. and the recalescent point at 676.4 deg. C., In this case the two points were separated by 48 deg. In the case of a high carbon steel the decalescent point was at 728.4 deg. C. and the recalescent point at 702.4 deg. or a difference of 26 deg. Now, as iron or steel is supposed to lose its magnetism, when it passes through the decalescent point and to regain its magnetism when it passes through the recalescent point, it is quite remarkable that Professor MacLaren should find the induction on heating the sample to be 6010 at 727 deg., and to find the induction on cooling the sample to be 6015 at 726 deg., which is practically the same thing. Perhaps a sample of steel when under the influence of an alternating magnetomotive force will have its recalescent point and decalescent point located at the same temperature. This is worth a trial for the physicists.

Professor MacLaren's second method of the direct measurement of hysteresis has the very great advantages of being applicable to an extremely wide range of induction, of giving the data, for plotting the hysteresis loop, in about ten minutes, and of being, to a certain extent, self checking (as the sum of the deflections for change of induction in one direction must equal the sum of the deflections for an equal change of induction in the opposite direction). It has the disadvantage from a commercial standpoint of requiring from three to four observers. Then, also, the reduction of the data and the plotting of the curves require considerable time. I believe the method could be made very much more rapid, as well as more accurate, by making it partly automatic.

It would be a simple matter to construct a recorder, whereby the galvanometer deflection would be recorded as a sinuous line upon a cylinder revolving uniformly with the time. The same recorder, or another one, could be made to record synchronously on another revolving cylinder, the change in the magnetizing force. From the two curves so drawn automatically, to a proper scale, the data could be taken for drawing the hysteresis loops. The delicacy of the galvanometer required would be no impediment to such automatic recording, as much more difficult problems, in the automatic recording of temperatures registered with very sensitive galvanometers, have been already solved commercially by myself and others.

It seems to me that progress in iron measurements should follow along the line of seeking greater rapidity in taking the data in methods of rapidly reducing the results, and in making automatic, processes now performed manually. To accomplish these results I can say with a certainty only requires capital and enterprise.

J. A. Capp: Mr. Robinson has described two sets of apparatus for measuring the hysteresis loss in sheet iron samples. A brief statement of about ten years' experience with the apparatus, using the bundle of 10 in. x ½ in. strips, in the commercial testing of sheet iron may be of interest.

The first and most obvious use of the test method was in the inspection of raw material and its testing to determine whether or not it conformed with the standard established in the specifications. Consideration of the many points which have bearing upon the preparation of purchasing specifications soon indicated that such specifications must define the required chemical composition of the steel and its manipulation in the rolling mill. At the time when this work was begun, the rolling mills were generally not equipped to make tests to determine the magnetic quality of their product but they did understand the chemistry of the steel and, of course, had control over mill processes. Experience shows that relatively hard sheets can be punched with greater ease to a given degree of accuracy than softer or thoroughly annealed sheets. It had long been recognized that heat treatment has fully as great an influence upon the quality of the sheets as composition. The use of the relatively hard sheets immediately then requires that the final heat treatment be done by the purchaser and it is obvious that the manufacturer cannot be held accountable for the results of a treatment applied by the purchaser and over which the manufacturer can have no control.

The next, and what has since turned out to be the most important use of this convenient means of commercial testing was the determining of the best treatment to apply to sheets to put them in a state having the maximum permeability with minimum hysteresis. This work was undertaken by selecting typical lots of steel from the standard commercial output of several manufacturers and from which lots of steel a very large number of 10 in. x ½ in. strips were cut. These strips well mixed, so as to be broadly representative of the lots from which they were taken, were made up into the one pound samples required in the hysteresis testing outfit. The hysteresis loss and permeability were determined for each of the samples and different samples were then carried through a long series of heat treatments, designed to indicate the influence of the rate of heating, the rate of cooling, the time the maximum temperature was maintained and of all the other variables which necessarily would enter into heat treatment of this character. In this series, thousands of samples were tested and the results when completed, indicated the desirable heat treatment of steels of the compositions and characters included in the lots selected.

This work provided the basis for the preparation of standard specifications which could be used by the purchasing department in their contracts for the sheet steel purchased. These specifications as already indicated, state the required composition of the steel and then define its manipulation by the producer, hence inspection testing substantially resolves itself into a matter of chemistry. But the question of proper mill manipulation still can be determined with reasonable dependence by the application of the prescribed heat treatment to the steel, when if the manipulation has been that specified, the hysteresis loss and permeability should equal at least a certain standard.

The necessity for heat treating the steel purchased at once requires that there be means of determining whether the prescription for heat treatment is actually being carried out in practice. The direct measurement of the temperatures used in the heat treatment is possible at least in certain parts of the furnace by pyrometers. It is obvious that a pyrometer can only measure the temperature of the particular point in the furnace at which it is placed and furthermore it is well understood that the indication of the pyrometer is more or less an average of the conditions surrounding its point of location. These considerations led to the use of hysteresis testing outfit as a check upon furnace work and an elaborate scheme was worked out for the exploration or the annealing furnaces by pyrometers and hysteressis test samples. Large numbers of the test samples were distributed throughout the annealing pots, as many as five or six hundred samples being used in one annealing heat. These samples had been taken from lots of material the history of which was thoroughly known and upon which the influence of varying heat treatment had been extensively studied. Hence the results obtained in the hysteresis outfit upon the test samples which had been distributed throughout the annealing pots enabled us, with reasonable accuracy, to determine the distribution of temperature in the furnace and pointed to the way to correct inequalities in this distribution, and to establish a routine for the furnace manipulation. This routine, when followed, is expected to yield uniform results, but hysteresis test samples are regularly used as a check upon furnace work, and the heat treatment operations are controlled through the joint use of pyrometers and the hysteresis testing outfit. Samples are placed in the pots at what experience has shown are apt to be the hottest and the coldest parts, and when the test samples show results below normal, the punchings in the particular part of the pot represented by these poor samples may be sent back for reannealing. Obviously the samples which are used in this way must be taken from stock which previous testing has shown will respond properly to the prescribed heat treatment, though it is but fair to say that almost no selection is required for this purpose, since the specifications provide a grade of steel which can be turned out by the producers with a highly satisfactory degree of regularity. Results are checked by tests upon samples taken from the actual punchings themselves and these confirm closely the results from the regular heat samples.

Still another commercial use may be made of a method of testing such as has been described. There are times when by reason of unusual service conditions, or because of unusually stringent specifications on the part of a customer, apparatus must be turned out which must be classed as special, because the core losses are required to be lower than in standard apparatus of similar design. In such circumstances, it is not always possible for the designing engineer to take care of the special necessities of the case in any other way than by the use of special material. Standard specifications provide material which, after proper heat treatment, may be expected not to exceed a certain maximum hysteresis loss. The average, however, is, of course, considerably below this maximum and there may be found exceptional lots which will run at a very low minimum. By having available a means of testing which requires but small quantities of material and the results from which can be quickly obtained, it is possible to go through stocks which could be used for the production of such special apparatus and select those particular lots which will run at or below the average. Advantage has been taken of this possibility in some of the rare cases where the designing engineers have been forced to require the use of specially selected material.

Mr. Robinson has discussed at some length the question of the general accuracy of the results obtained with the outfit using the 10 in. x ½ in. specimens. Experience has shown that when a line of machines has been designed using material which has been tested extensively by this method and which machines after completion have been put through the usual tests, the designing engineer is provided with data upon which he may determine within close limits the core loss of machines of new design. We were at one time able to determine from tests made on the 10 in. x ½ in. samples that the manufacturing processes of one of the sheet steel mills had gone astray. Had we not been able, at least with a very close approximation to accuracy, to make tests upon a large number of samples so as to determine that it was actually temporarily characteristic of the output of that mill that we could not get the expected results, we would have been forced to work in the dark and probably would not have been able to prevent the use of a good deal of poor material in commercial apparatus. We were able so to impress the mill representatives with the results shown them that they made an investigation only to find rather to their astonishment that a supposed improvement had been made in the process by a man in the mill who had not thought it necessary to bring the change to the notice of his superiors.

When the apparatus was first set up for use, there was some doubt whether readings could constantly be duplicated on the same samples. Therefore, a number of samples representing a wide range of results was tested and laid aside under lock and key. These were taken out at irregular intervals and tested for a period of some two or three years. The greatest variation found was not over one per cent which, of course, is considerably less than the normal variations to be expected in a large number of tests representing one particular lot of material.

The foregoing has shown that a very considerable commercial use is being made of the testing outfit described. This extensive use, however, is made possible only by reason of the speed with which results may be obtained and by the comparatively small weight of material which is required in the test. Mention has been made of the use of the method as a check upon the material received to indicate conformity with specifications, and as a check upon the heat treatment applied in the annealing furnaces, which check is accomplished not only by the testing of the samples which are prepared and placed at predetermined points in the annealing pots but also by tests upon samples punched from the material actually annealed. Tests of the samples are made not only before and after treatment, but also upon a considerable proportion of them after subsequent exposure to moderately elevated temperatures to determine the amount, if any, of increase in hysteresis due to what is commonly called aging. This together with experimental work, requires the testing of an average of about 600 samples per week. The samples are delivered to the laboratory in the form of loose strips 10 in. x ½ in. These must be assembled into the one pound bundles, the top strip of which is stamped with an identifying number. The bundles are weighed and the necessary data entered in a record book. The samples are then turned over to the furnace men by whom a record is delivered to the laboratory showing the location of the several samples in the various pots. This data is added in the record book, together with the results of tests before and after heat treatment and aging. Results are then entered on a blank report form which is sent to the parties who must know the detailed results.

Mr. Robinson has briefly referred to the necessity for economy in the use of material where a large number of tests is to be made. This is obvious when it is considered that the test samples are not of suitable size or shape for productive use, and hence may become an item of expense worthy of consideration. Furthermore, room in annealing pots may not be taken up unduly by test samples without reduction of productive capacity, hence the test samples must be small in volume and of such shape that they may readily be placed in the annealing pots without interference with the regular production material. Special shearing devices have been provided for cutting the 10 in. x ½ in. strips so that the waste of iron is at a minimum. We have stated that there are an average of 600 tests per week made and reported. Some of these tests are repeated on the same sample so that there are actually required about 500 samples or an equivalent number of pounds. Each sample consists of an average of 52 strips of fourteen mil iron. Hence, there are about 26,000 strips of iron handled per week in making up the samples. Obviously, if the sample were larger than that now used, the weight would be increased proportionately as well as the cost of material consumed, and labor of handling.

From all this, there may be formed an idea of the amount of labor involved in the testing and clerical work. Perhaps the best indication of the speed with which the work may be done is the statement that all of this work is carried on by two men who have time left to do the laboratory annealing experiments which are constantly in progress.

L. W. Chubb: The magnetic testing of sheet steel had been a very active subject for the last few years, especially during the development of the silicon steels. I have no formal notes on these papers to-night, but some points have come to my attention that I would like to ask some questions about. Is it not true that the use of windings of iron wire, referred to in Professor MacLaren's paper, is a source of error If, when the temperature gets high, the permeability is very much reduced, excessive exciting current in the iron wire would cause distortions of the induced voltage and the flux in the sample. Such distortions would apparently lower the hysteresis loss and be caused by decreased permeability, even though there would be no decrease in the area of the true loop of the steel. It would seem as though the combined resistance and inductance of the iron winding would cause drops and distortions, resulting in hysteresis errors of several per cent. No data has been given for the high induction points at high temperatures, and I therefore assume that reduction of permeability was a limiting feature. I would like to ask Professor MacLaren if any results were taken showing the relation between permeability and temperature.

Mr. Robinson's paper treats of testing methods that need to be carried on very extensively in a large commercial factory. In our work we use a single method with a sample which is between the one pound sample and the standard Epstein sample described in the paper.

In certain work it is the custom to use steel without annealing after punching, and the sample consisting of small strips 10 in. x ½ in. does not give a representative result for the steel. The variations in a commercial sheet of steel are as great within the sheet as between separate sheets, and therefore the test with the small sample is not satisfactory, not only because of the damage due to cutting small strips, but also because such a sample does not sufficiently cover the area of a commercial sheet. To get a representative one-pound sample from a sheet or lot of steel, it is necessary to resort to some complicated scheme of cutting, which is laborious and wasteful of material.

Our Epstein apparatus uses samples of fifteen pounds of strips 15½ in. long by 1⅜ in. wide. The results obtained with the 15-pound sample check results obtained with the standard Epstein samples. Several details in the method are different. The first I will mention is the use of a secondary winding. In our apparatus we take the potential for the wattmeter coil and for the voltmeter directly over the exciting winding. This includes in the wattmeter reading the $I^2 R$ loss in the windings. The voltage drop in the winding also tends to reduce the measured core loss.

At first sight it would seem inadvisable to introduce such errors in the testing method, but we have found by very careful ballistic exploration of the Epstein sample that the error due to the leakage at the corners is greater than the resultant error caused by the $I^2 R$ loss and the $I R$ drop in the winding. Since resultant copper error and the leakage error are in the opposite direction, and are both functions of the permeability of the steel, they will always cancel the effect of each other to a certain extent, and when the coils are properly proportioned the method will give better results than when a secondary winding is used.

Dr. Sharp brought up the point that the results in Professor MacLaren's paper given by the ballistic method and by the wattmeter method do not agree exactly. Mr. Robinson shows in his paper a rather close agreement between the two. Many researches on the comparison of the wattmeter and the ballistic methods have generally shown the ballistic results to be lower than the hysteresis part of the wattmeter results, which seems to be correct.

When flux grows in a lamination of finite thickness the eddy currents will cause a skin flux, and the induction will not grow with uniform rate throughout the lamination. This will result in a variable maximum induction and increased hysteresis loss.

Work done by Dr. Lloyd shows that only when the laminating of the steel is very fine will there be a close agreement between the hysteresis loop taken ballistically and the hysteresis per cycle, taken by the wattmeter test. I believe that the reason Mr. Robinson's results check as close as they do is because he takes his voltage from a secondary winding, and the leakage error causes a reduction in the measured loss.

Mr. Robinson states in the paper that the flux variations due to leakage amount to not more than eight per cent. I assume that he means variation at an induction of 10,000 lines. Exploration of the sample under direct current excitation has shown that the leakage at the corners is very much greater and the resultant error to be more than one per cent. The design of Mr. Robinson's apparatus, the Epstein apparatus, is novel, and I believe it is a very fine scheme. We use corner blocks and clamps similar to those shown on the Epstein set in Fig. 4.

Repeated tests have shown variations between the results obtained by different operators, while the same operator can test a sample repeatedly and get the same result. The variations were found to be caused by differences in clamping the corners and pounding the corner blocks. I believe the clamping scheme shown in Fig. 5 is a great improvement over the usual Epstein corner blocks, and will do a great deal toward eliminating the personal equation in testing with a given set of apparatus. The other advantages mentioned in the paper are also of great importance, and make the adoption of the new clamping method seem advisable for standard Epstein apparatus.

R. B. Treat: A comparison of the two pieces of apparatus indicates that testing by means of the one pound sample is economical only for sheet makers or users who require many tests per week. The 10 kilogram apparatus is the more economical for a few tests per week, or infrequent tests, because of the use of commercial instruments which are available for other tests and are returnable to the makers for repairs and good results can be gotten by the average operator. The one pound apparatus requires the maintenance in usable condition of infrequently used special instruments, a thing very annoying and expensive. The high cost of material in the 10 kilogram samples is a disadvantage, but is to be preferred to the special instruments of the one pound apparatus.

Mr. Robinson takes it for granted that we are familiar with many of the minor details involved in the tests. It may be well to mention the importance of a few of them. Users of steel find it necessary to check the quality of incoming material with the supplier's guarantee and with specification. The samples should be sheared but unannealed, unless there is an agreement with the supplier that he will accept annealed tests. Ordinarily the purchaser of sheet steel must be able to test the suppiled material without subjecting it to any questionable process, such as punching or annealing. Some so-called annealing is ruinous to the material.

Users of steel require also to know the properties of the material when incorporated in the finished apparatus. For this information the samples may be either sheared or punched, but should receive an annealing identical to the usual manufacturing process.

Mr. Robinson chooses a width of sample such that the effect of shearing is small, but while small in a sheared sample it may be very large in a punched sample, for these reasons: Shearing must be a clean cut, or there will be no cut at all, while a punch may cut cleanly, or it may mechanically disturb the metal for a considerable distance from the edge of the sample.

Samples can be japanned or shellac coated at a very small cost, so it is advisable to do this and thus minimize the effect of fins on the edges. Japanning increases the weight of the sample about one-half of one per cent, depending upon the thickness of the coat. Annealing may change the specific gravity of the sample, under some conditions it increases the weight about two-tenths per cent both dependent upon the exposure of the sample to the annealing heat.

It would be well to settle upon a method of determining the cross-section of the sample, and consequently the value of " B ". This should be calculated from the weight and the longest dimension, for the percentage of error in taking this dimension is least of all.

It is very unreliable to micrometer individual sheets or even a squeezed pack.

Area determined by weight, and that by linear dimensions, may differ by ten per cent. The weight per cubic inch of silicon steel is about 0.271 lb. and common steel is about 0.275 lb., one and one-half per cent difference.

The butt joint with its paper insulation, has the advantage over the lap joint in that the flux is less likely to pass through the sheets at the joint, which might set up local eddy currents. The butt joint however causes leakage which has the effect of apparent higher core loss. This is easily demonstrated by successive tests with varying insulation in the joints and has been discussed by the Washington Bureau of Standards.

The Magnetic Committee of The American Society for Testing Materials has given the subject of sheet steel tests considerable study and we may hope it will soon settle upon a standard method for the use of both the maker and user of electrical sheets.

W. J. Wooldridge: Several speakers in referring to Prof. MacLaren's paper have spoken of the probable errors due to the use of iron wire for winding. The paper as a whole seems to fill in a gap in our knowledge in regard to steel.

It would perhaps be interesting to bring to your attention again the fact brought out by Ewing in his book on Magnetic Induction of Iron and other Metals, in which he points out that the permeability at very low inductions increases with increasing temperature up to 775° C. and then decreases very suddenly between 775 and 786 deg. cent. At medium intensities that is less marked, while at high intensities the permeability falls off continuously, it does not increase as it does at low intensity—but falls off continuously, and falls off more rapidly at the end. In this connection it has been a question in my mind, and the minds of several people I have talked with from time to time, as to whether there was really some relation between hysteresis loss of high density and permeability. We know that at low densities there is no such relation, because with an alloyed steel, the permeability at very low densities is very much better than in standard iron, but these permeabilities cross somewhere about 12,000 *B*, if I remember rightly, and it has been a question whether on densities over that there is or is not some relation between the hysteresis and the permeability. The results of this test would apparently show that there is no such relation, and therefore this paper fills a gap on a point concerning which we did not have definite knowledge before.

As near as I can make out in table III, the logarithmic relation between the hysteresis loss at various densities does not follow the 1.6 law. One of the speakers has mentioned that the eddy current loss does not vary as everybody supposed it would, *viz.*, that it should be stated as varying inversely as the specific resistance. The eddy loss in ordinary iron, at normal densities and frequencies is, roughly, 30 to 35 per cent. Silicon steel has between four and five times the specific resistance of ordinary iron, but the eddy loss is reduced only to 18 or 20 per cent, which does not follow at all the supposed law in regard to specific resistance.

W. R. Whitney: In the Research Laboratory we have found, after considerable experimental work, that it is desirable to employ as small samples as practicable for test. The reasons are almost obvious. Small samples of new material are usually much easier to obtain than large ones. Experimental work on these samples, such as heat treatments, compression and bending experiments, etc., can be more easily performed than on large samples. A relatively large number of separate samples can be taken from a small sheet of iron, and by taking the average of measurements on many small samples, results are sometimes obtained which would be concealed by the measurement of the hysteresis of the same quantity of iron in a single sample. For this reason we have often used a Ewing tester, where separate measurements were made on each ounce of iron, and have followed up the leads opened by such tests, by means of the standard factory one pound samples. In experimental work it is very important that all unnecessary barriers be removed from the way of quick and easy production of samples. It is preferable if the iron can be cut, annealed and tested in the same room and by one man.

Samples must also be capable of quick and simple measurement, and finally, large numbers of the identical tested samples should be kept on hand for later reference.

This is all very easy with one ounce samples, but the Ewing tester, in our hands, is little better than a qualitative instrument, so that we have always referred to one pound samples for accurate conclusions. Such samples are also still small enough so that care and storage of them is not a serious matter. When the tests are made on twenty-two pound samples, it becomes evident that even the cost of the samples themselves is a factor where much testing is to be done. To make many tests in one day or to store identical samples in any quantity becomes a burden, if they are too heavy.

C. J. Fechheimer: The methods which have been described this evening for testing iron are applicable principally to transformers, in which the distribution of flux is very similar to that which obtains in the samples. They cannot, however, be used directly in dynamos or motors because in these there are heavy pulsations of flux and the distribution of flux in the core is by no means uniform and is quite different from that which we generally assume. The rapid change of flux which takes place when the edges of the poles pass under the armature teeth (or the armature teeth pass under the poles, whichever the case may be) also materially affects the loss occurring in the teeth. The result is that the core loss is two or three times as great as we would determine ordinarily by the constants obtained from transformer tests.

One of the speakers said this evening that the tests made in the factory on samples of new grades of steel are used for laying out a new line of machines. This, I believe, should be the case to a limited extent only, but I would be inclined to question it, because the transformer tests are not necessarily indications of what may be expected when the same steel is used in the armature cores of generators or motors.

For example, we know that while silicon steel has an eddy current loss, measured by means of transformer tests, which is considerably less than that of common steel and has also a slightly lower hysteresis loss, yet this steel does not have any appreciably less loss in generators or motors than the common steel. I questioned the results of the tests for sometime and had them repeated and was finally convinced when the temperatures indicated that the core loss as measured was correct.

There were six turbo generators of a certain size built, three with silicon steel and three with common steel, and the loss seemed to be about the same in all cases. There was, of course, some slight variation, but this variation was not any greater than that which usually occurs in duplicate machines built with the same quality of iron. I have never been able to account for this discrepancy and I should very much like to have an expression of opinion from some of the members to help clear this up.

Then there is another point which we find in practice does not agree with theory. We usually assume, and without doubt correctly, that the eddy current loss varies with the square of the frequency and the square of the induction density. The hysteresis loss varies with the first power of the frequency and approximately with the 1.6 power of the density. However, I have found that the total core loss in machines varies from 1.9 to 2.2 power of the density, which would indicate that all the loss is due to eddy currents. Nevertheless when we compare the loss at different frequencies on the same machine we find that the loss is proportional to about the 1.4 power of the frequency, which would indicate that a great deal of the loss is due to hysteresis. This is another discrepancy for which I have never been able to account.

I should like to ask Professor MacLaren whether the iron did not age when starting with 25 cycles, repeating the tests at 60 cycles and then going back to 25 cycles. It would seem that the alternate heating and cooling of the samples causes the constants for the losses to be affected; that is, the iron would have aged.

C. A. Adams: At the recent mid-year convention at Schenectady, Mr. W. J. Wooldridge presented experimental data showing that the exponent of "*B*" in the Steinmetz formula for hysteresis loss was not a constant for modern silicon steels, but varied from about 1.5 at low densities up to 2.5 or more at high densities. The results of Prof. MacLaren's experiments seem to show that up to the highest density used by him, the exponent was 1.6 and practically constant throughout.

It is certainly very desirable that this apparent discrepancy be explained, for if both exponent and coefficient vary over a wide range, the Steinmetz law is not applicable to silicon steels.

W. S. Franklin: If the engineers concerned in making measurements would make a distinction between and use two distinctly different words for the two classes of errors, it would help us very much in regard to discussions of measurements of such things as hysteresis loss in iron. There are two distinct kinds of errors which physicists recognize, namely, errors due to the wabbling of the measuring instrument, and errors due to the inherent lack of constancy or definiteness of the thing you measure; and I think we should call the first of these errors, speaking of the probable error of a set of observations; that is, the things which are inherent in our methods and instruments, and the other things we should call departures. We could speak of "probable departures", etc. Take, for example, the main load factor of the consumer of electric lights who has fifty lights installed. We will say that the main load factor of that kind of a customer is 60 per cent. Now, as a matter of fact, there are enormous departures from that. If you were to take a large number of individual cases, you could determine what the probable departure is, for that probable use, if used in the same sense as we use probable errors. I wish we could get into the habit of distinguishing clearly these two kinds of errors which enter into numerical measurements; one is external error and the other is internal error, and we might call one " error " and the other " departure ".

Malcolm MacLaren: In answering Mr. Sharp's question, regarding the use of iron wire, I would say that that was taken as a matter of convenience. It did not seem as though copper would be suitable to stand the high temperatures, and iron was the most convenient substitute. The wire was about one-sixteenth of an inch away from the sample, No. 18 wire used, the turns being spaced about one-eighth of an in. apart, so that with the large cross section of the sample it would seem that the error due to the additional iron in the wire would not be considerable. If extreme accuracy was aimed at, it would be probably better to use some other material such as nickel.

As to the ease of manipulating the apparatus in making the loop, I believe that it will be found that taking men who have not made loops before, they will find it much easier to accommodate themselves to this manipulation of the resistance than to making the observations with the ballistic step-by step method. As an indication of the flexibility of the method we recently took loops varying from an induction of about 200 B up to about 14,000 B, in which the only change required was to vary the resistance in the galvanometer circuit, so as not to take too many points in tracing the loop through its cycle.

As to the lack of agreement in the measurements by the loop method and the two-frequency method, I can not explain slight discrepancies that occur except to say that at the lowest induction where the greatest discrepancy occurs the wattmeter deflection was too small to read accurately. I believe that the results presented by Mr. Robinson this evening are certainly a sufficient justification for the use of the two-frequency method in making such measurements.

Dr. Northrup speaks of the number of observers required to make the loop measurements. The loops presented in the paper were taken with two observers, it is a little easier, however, to have three, one to take the time, and read the ammeter, one to change the resistance, and the third to read the galvanometer.

Mr. Chubb speaks of the losses that would occur in the use of iron wire, but I think these have been largely eliminated by the use of the second coil which avoids the necessity of correcting for the $I^2 R$ loss and for the $I R$ drop. In addition, the currents were kept very low throughout the experiment, so that the distorting effect was small.

With regard to the change in permeability, this was not observed with any particular care. It was noted, however, that the change at the higher inductions was very small, until the higher temperatures were reached. Above 650 or 700 deg. cent., the permeability fell off very fast.

In reference to Mr. Fechheimer's question regarding the method of making the measurements, the temperature was not allowed to fall at any time during the measurements, it was simply held constant for a sufficient time to take a set of readings, first at 25 cycles, then at 60 cycles, and then a few check readings at 25 cycles, so that the check readings would generally be taken less than ten minutes later the original readings. The sample was then allowed to heat up to the next point.

With reference to Dr. M. G. Lloyd's method of deriving values for the exponent of B in the expression for hysteresis loss, $w = a\,B^x$ I would say that the usually accepted interpretation of this expression is that the hysteresis loss in any magnetic material may be represented by a *constant* multiplied by the induction raised to an unknown power. If however the exponents given by Dr. Lloyd be used for the determination of a its value is found to be variable even with constant temperature. For example, using his figures in Table II for 218 deg. cent. a varies from 0.635×10^{-6} to 1.49×10^{-5}. These revised tables which he presents appear therefore to have no physical significance. My reason for taking 1.6 as the value of the exponent at the lower inductions was that these samples were admittedly not as advantageously designed for obtaining extreme accuracy as would have been possible if the windings had not been arranged to stand temperature up to 800 deg. cent. and numerous other investigators had obtained this value for ordinary steel at inductions near 6000 B. Also the results that had been published upon silicon steel while not entirely convincing indicated that this value of 1.6 was correct for inductions near 8000 B.

With regard to the possible effect of eddy currents in the determination of the hysteresis loop I would call attention to the fact that the samples were well laminated and that the time of reversal was over five minutes so that the eddy current could not be large. It was possible however to detect their presence and estimate their effect by holding the magnetizing current constant for a few moments during a reversal and noting the galvanometer deflection. The correction due to this cause could not well amount to more than the width of the line bounding the loop.

L. T. Robinson: With reference to the points that have been brought up about the variation of the hysteresis exponent, it was certainly very interesting to see that Professor MacLaren got the original 1.6 power results, whereas some of the rest of us have got something quite different. Whether the explanation is that which Mr. Chubb gave, that there may be certain irregularities in the tests which Professor MacLaren made, and we are right, or that the 1.6 is right and we are wrong, I do not know, but I think that is something that perhaps can be straightened out within a short time, at least I hope so. I have a great many results, and I am trying to work them up now and see if I can make anything out of them.

About the ballistic method, and the agreement, etc., between the two methods of measurement, I think I covered that in a fair way in my paper. I do not know whether it should agree, or whether it should not agree. There are so many things about the behavior of iron in magnetic fields that we do not know, that I do not think we should be too positive about our statements. I am satisfied to say that we usually have looked on the ballistic method as a good way to make the test. It was the standard method, and in developing another method we simply looked back to the old method to see how it agreed. There is a fairly good agreement, whether it means anything or not, I do not want to say. I hope it does, but we are not by any means sure of it, until such time as we can explain some of the vagaries with reference to the separation for eddy currents at different densities. The whole thing is founded on certain assumptions, some of it I hope is true. They all of necessity cannot be true. If you start in to discuss the whole subject and proceed to the final analysis along known lines, you cannot go very far. You assume that the eddy current loss varies as the square of the frequency. When you say that you say that it varies as the square of the voltage produced. When you say that it varies as the square of the density, you say the same thing, but still when you try to separate using various densities, it does not work. You cannot separate by change in density, although you can separate and get a straight line by changing frequency. Whether the fact that you get the straight lines means that you get the correct result or not, I think we can by no means be sure we are correct in saying. There is an opportunity for something to be said about this subject that has some definiteness about it that our present statements must lack, because of our want of absolute knowledge.

With reference to the long period D'Arsonval galvanometer, with considerable damping, old and new are only comparative words, I would say that we have used such an arrangement since 1898, to the best of my recollection, and I believe it to be good.

The Koepsel apparatus referred to is perhaps not directly connected with the subject matter of the evening.

I believe that it was brought out first in this country and published in the *Electrical World* some time in 1894. It is said to have been brought out sooner than that by the one whose name is now applied to it—but I think it was not published until some time after.

With reference to using insulation between the sheets, I think it is not necessary to insulate alloy iron but it may be necessary to insulate standard sheets.

I believe Dr. Sharp spoke of the disagreement between tests made by another method and by the apparatus that has been developed by the Bureau. My remarks on the elegance of that method were based almost entirely on the results that were obtained with it regardless of the comparison with other results —that is, it seems to be very good, because they get very nice separations, and the things that vary more in other apparatus seem to vary less in it, and therefore I thought it was very good.

I think the matter of the standard sample has been quite generally referred to as being desirable. I was much interested in Dr. Northrup's remarks about the transformer running at 200 deg. cent.—we may have something like that some time, but the most interesting thing is what would he use for the insulation. That information is somewhat incomplete.

With reference to Dr. Franklin's remarks about errors and departures, I think that is a very good distinction, but it is hard to tell which is which. You do not get anything just right—sometimes you know you are wrong, but do not know whether it is an error or a departure.

With reference to Mr. Chubb's remarks, there is nothing more than a slight difference of opinion on what seems to be a minor point. I appreciate the fact that results can be obtained accurately by the method that he prefers. I may be wrong in thinking so, but it seems to me it is better to do something that is more generally applicable than to choose some arrangement for matching one error against another in a specific device. However, the specific point brought up as it relates to any apparatus except that described in the paper I have not covered experimentally, and cannot, therefore, be very definite in expressing an opinion on it at this time.

With reference to Mr. Fechheimer's remarks, it is interesting to know that some one has found some things that he cannot explain. We have been finding them right along, and it would be very easy to write a paper on the things about iron that you have tried and seen, and could not explain.

Henry Pikler: We are engineers, ultimately interested in the performance of sheet steel in the finished apparatus. If different makes of electrical machinery were built of exactly the same quality of sheet steel, we would find that the total iron loss per pound of sheet steel in these machines would not be the same, although the magnetic densities and frequencies are kept the same. This is due to differences in the design and construction between the electrical machinery of the various makers. In other words, if a given quality of sheet steel be used for building the transformers of makers " A ", " B " and " C ", we would find that the total watts loss per pound, at the same magnetic density and frequency, would be different in these three transformers. If instead of transformers we consider generators or induction motors, we would find that these differences would be much greater.

From this it follows that in order to foretell the total watts loss in the finished electrical apparatus, it is not sufficient to know only the core loss watts per pound in a sample of sheet steel tested by some standard method; the figure obtained by the standard method must be multiplied by a coefficient.

The difficulty lies in establishing a method of testing samples which can be used as a standard. I wish to emphasize that, for the reasons pointed out above, I do not consider that it is of primary importance at all that by the standard method physically accurate core loss watts per pound may be determined, but that by using this standard we should always get exactly the same result, whether the test is made by Peter, or by Paul, in the United States, in Japan, or in Germany. I would go even further and state that it is not a core loss—that is, a watt loss measurement—which is necessarily the criterion of the quality of the steel. To illustrate my point by a drastic example, I mean that if for instance a certain sample of steel, under the conditions created by the standard method, be struck and it vibrates say so many times per second and between this number of vibrations and the total watts loss there is a definite relation and finally *this* standard method can be exactly duplicated everywhere and at any time for the purpose of obtaining uniform results, then this method is more desirable than one which is based on watt measurements and gives not so uniform a result.

Probably the most important function of a standard method is to establish a basis in the transactions between the purchaser and supplier of sheet steel which excludes any chance of dispute. It is my opinion that there is a greater necessity for establishing a standard to this effect, one that gives uniformly correct results within say 2 per cent than to have this method for the purpose of enabling the designer to predict the core loss in his machine within that limit. Because I consider the uniformity of the results the most important, I naturally do not favor the introduction of any element into the standard method which is liable to introduce variations. For this reason I am very strongly opposed to any method of testing iron for the above purposes for core loss where the magnetic circuit of the test piece is broken by joints of any kind.

In reference to several remarks and questions brought up in connection with " core loss ", which pointed out that the core loss of induction motors or turbo generators, etc., cannot be predicted, and furthermore the relations between watts, magnetic density and frequency do not follow the law given by the equation $W = M\,(B \backsim)^2 + N B^{1 \cdot 6} \backsim$, I wish to give my opinion as follows:

In order to investigate these problems the engineer must become a physicist. Unfortunately, according to my observation, very few become such in their investigations. One of the most fundamental principles of physical investigation consists in attacking the problem step by step and these steps should be extremely small. A phenomenon, as it appears to us at first glance, is in reality a complexity of very many phenomena and we will not be able to understand the whole if we fail to recognize the details.

Take the simplest electromagnetic apparatus, the transformer. There the engineer assumes a uniform flux density as the underlying basis of his calculations, derived from the terminal voltage, frequency, number of turns and the dimensions of the core. The truth, however, is that in any commercial transformers, even with the best magnetic joints, such is not the case. The magnetic flux is the densest at the magnetic center, which is the center of the magnetizing winding and there the volts per turn are also the greatest. In either direction, away from this center, the density of the magnetic flux, and with it the induced electromotive force per turn of the winding, will diminish. Whereas in the neighborhood of the magnetic center the lines of force travel in the same direction as is the direction of the "mechanical" magnetic circuit in that region, in the neighborhood of the joints there will be many lines of force which will depart from the steel and will cut it transversely. Right at the joints this transverse cutting of the plates by the lines of force leaving them will be a maximum. This will introduce additional losses in the steel, mainly eddy losses, the magnitude of which depends upon the perfectness of the joint and the distribution of the winding over the core.

In considering, instead of a closed magnetic circuit of a transformer, the magnetic circuit of a generator or motor, we find the situation much more complicated. In these machines the irregular distribution of the magnetic flux is established even on purpose (low regulation, small slip, etc.). In these machines the transverse cutting of the core plates by the magnetic flux is very greatly pronounced. It is therefore a great mistake to expect to derive any conclusions as to core loss watts from measurements based on conditions where the magnetic flux travel in the direction of the mechanical magnetic circuit. Before trying to establish a relation between watts core loss and magnetic density derived from impressed or induced e.m.ts., turns and frequency, it is of primary importance to investigate the geometrical configuration of the path of the magnetic flux. This can be done either by exploring coils, or even by simple reasoning, based on experience, going step by step over the entire magnetic circuit and predicting the probable path of magnetism in order to get the geometrical configuration of the lines of force.

When we look at magnetic circuits, flux densities and core losses in this light, I think we shall be surprised to hear anybody expect a connection between core loss and magnetic density as derived from volts impressed, turns, etc.

M. G. Lloyd: It is highly desirable that some method of measuring hysteresis suitable for commercial conditions should be standardized in this country, for the convenience of manufacturers and buyers. The American Institute of Electrical Engineers could well take the initiative in this matter, as has been done by its sister society in Germany. There the Epstein method has been adopted and seems to give general satisfaction, the standard test being at 50 cycles and 10,000 gausses. Perhaps the details of the Epstein method could be revised so as to be more acceptable in this country, but its predominant features should be retained for a standard comparison method. Where shop conditions make other methods desirable, they can of course be used, the standard method being resorted to only for occasional comparisons, and to check up results against those obtained by outside parties. The more accurate methods available by the use of properly proportioned rings or such apparatus as that in vogue at the Bureau of Standards are more especially suitable to investigations aimed at a correct value of the physical constants, and similar tests where accuracy is more important than economy in time, in materials or in the necessary apparatus. It is important, however, that any method adopted as a commercial standard should use a specimen of such dimensions that the hardening effect of the cut edges is small, since it is not always feasible to anneal after cutting, and indeed, unless annealing can also be standardized (a difficult matter), results obtained by different observers at different places would not be comparable. It is well recognized that the process of annealing is quite as important a factor in determining the properties of the material as any other factor involved. It is desirable also that the method should be adapted to the use of portable measuring instruments. This requires the use of a large sample, and it suggests the use of a good magnetic circuit in order to keep a fairly high power-factor. The Epstein method seems to have best met conditions generally found, but where it is necessary to make a large number of determinations in a short time, such a method as that described by Mr. Robinson is decidedly superior for the workshop. It gives comparative values with sufficient accuracy and has the advantage of using less time and material.

It is to be regretted that Mr. Robinson has said nothing about the application of his method to silicon-steel. Silicon-steel is usually used at higher flux densities than ordinary steel, and at the higher flux densities it requires a much larger magnetizing current, making a lower power-factor. In Mr. Robinson's method the magnetizing current must be large enough to induce the flux at the center of the specimen, and this may be 40 per cent higher than the nominal value of flux. The conditions are therefore much less favorable with silicon-steel than with ordinary steel.

The paper by Professor MacLaren is of great interest in showing the manner in which hysteresis varies with temperature. Caution should be observed, however, in attaching too much weight to the accuracy of his measurements. When the form-factor is not determined in the wattmeter method the results must be viewed with suspicion. Evidently the form-factor was not determined in these experiments. Even supposing that the voltage wave of the generator was sinusoidal, it is not likely that the secondary electromotive force, whose form-factor enters into the computation of flux density, would have the assumed value. This is especially true since iron wire was used in the magnetizing coil and its resistance was probably high therefore, and moreover variable with temperature. Since the voltage used and the resistance of this winding are not given, it is impossible to judge of the amount of distortion probably present.

The values given for the exponents which represent the power of flux density which is proportional to the hysteresis are very misleading. In the first place they depend upon the assumption of 1.6 for one condition, and a computation based on this value for the other conditions. Moreover a very undesirable method has been used in making the computation. As a matter of fact the exponents vary through a wide range, from values less than unity to as high as 1.99, as will be seen in the accompanying tables, which have been computed for specimens two and three. In fact, at a temperature of 700 deg. the value is actually negative for silicon-steel, since it is to be observed that the hysteresis found at 8,000 gausses is greater than the value found at 10,000 gausses.

Professor MacLaren has computed his values by assuming 1.6 at the lowest flux density and used this value to determine the constant a, and the resulting value for a is used in computing the exponents for all other flux densities. In the tables which I have computed the exponent is found by means of the equation

$$x = \frac{\log w_1 - \log w_2}{\log B_1 - \log B_2}$$

and the value of the exponent therefore depends only upon the values found for the hysteresis at two values of flux density and the coefficient a is assumed to be constant only between these two points.

In the tables each value applies to the range of flux density between the value which it is opposite and the next preceding value. It will be seen from these tables that there is no regular variation in the value of the exponent, except that for silicon-steel at all but the highest temperatures the exponent decreases with increasing flux density. This result is in contradiction to most of the other experiments which have been made; most observers have found it to vary in the opposite direction. Reference may be made, for instance, to the paper by Mr. Wooldridge, at the Schenectady convention. As experience in this work has shown me what large errors may be produced in the result by small variations in the form-factor, it seems likely that these results are not very accurate and they are principally valuable in showing the general trend of hysteresis loss with temperature. In this connection it should be remembered, too, that at high flux densities the permeability decreases with increasing temperature. The magnetizing current would therefore increase and at the same time the resistance of the magnetizing circuit is increasing, so that the distortion would increase at a rapid rate.

The table given in the paper, showing the variation in induction with change in magnetizing current near the recalescence point, is chiefly valuable in showing the great rapidity of variation in that region. The differences found with ascending and descending temperatures are not significant. The two curves start very sharply at the same temperature of 737 deg. and cross at about 721 deg. An error in the measurement of temperature of three deg. would account for any difference found between these points. Since the variation of permeability with temperature is very different for different magnetizing forces, it is necessary to use a wide range of magnetizing forces to make such experiments of much value.

It is interesting to observe that the method used by Professor MacLaren for hysteresis loops can be used with small samples, as it has been generally supposed that this method was only applicable to cases in which the cross-section of the material, and consequently the flux, was very large. This method can hardly be claimed to have the accuracy, however, of the step-by-step method. Since the continuous change in flux will induce eddy currents which continue during the entire half loop, and since they oppose the main magnetizing field, the observed value of H will be too large. The extreme points of the loop will be correctly found, since the current becomes constant at these two points, but in between them the loop will be broadened, and the value for hysteresis will be too large. The result is similar to that found by the wattmeter method in a case where the eddy currents are small and are neglected. It is to be noted that in two of the three cases given, the loss is larger by this method than by the two-frequency method, although in the third case it is smaller by five per cent.

Dr. Sharp has called attention to the recent paper in the PROCEEDINGS of the Institution of Electrical Engineers in which the method used at the Bureau of Standards was reported to give results too high. I should like to call attention to the fact that the comparison was not made with the Epstein method, but with a different method whose accuracy was entirely unknown, although it was used as a standard of comparison. The only value of that research is in showing the differences found in the two methods.

It is sometimes wondered by those designing and testing electric machinery that the values of the exponents of flux density which are found in laboratory experiments, or computed on theoretical grounds, do not apply in practice. It would really be more wonderful if they did. Such an exponent as 2.0 for eddy currents, for instance, is computed on the assumption of uniform density in one definite direction in a sheet of infinite width. In dynamo and motor cores none of these conditions are fulfilled, and even in transformer cores we do not have uniform flux density. The demagnetizing effect of the eddy currents makes the flux less at the center than near the surface. With increasing flux density or increasing frequency this effect is intensified and results in the eddy currents increasing at a less rate than the square of either of these quantities. As shown in Mr. Wooldridge's paper at the recent Schenectady convention, the exponent for eddy currents is actually found to decrease with increasing flux density, and such a decrease is qualitatively explained by the above consideration. It must be remembered, however, in connection with the determination of eddy-current losses, especially in silicon-steel, that they form a small part of the total loss, and accurate determinations are extremely difficult. Small errors in observation, or small departures in the wave form, may produce large errors in the value of exponent found.

In the cores of generators and motors, the flux density does not simply alternate in direction, and the relative distribution of flux is not constant. The flux pulsates in space as well as time. The laws of hysteresis and eddy-current loss which obtain with the usual testing apparatus cannot be expected to apply even approximately under such conditions.

TABLE II

B	Temperature in deg. cent.							
	218	237	358	445	527	597	660	707
6000								
8000	1.53	1.60	1.64	1.63	1.77	2.08	1.92	1.99
10000	1.87	1.68	1.68	1.69	1.70	1.54	1.57	1.25
12000	1.81	1.72	1.60	1.61	1.62	1.24	0.85	0.94
14000	1.94	1.72	1.62	1.38	1.31	1.14	1.41	0.60

TABLE III

B	Temperature in deg. cent.					
	47	300	402	508	597	659
8000						
10000	1.79	1.66	1.48	1.04	0.74	0.52
12000	1.68	1.44	1.36	0.96	0.60	1.425
14000	1.54	1.37				

J. D. Ball: In regard to the iron tester for 10 kg. samples 50 cm. by 3 cm., it might be well to add some data as to how satisfactory it has proven in actual practice. Regular checks are made between three laboratories: one located at the steel mill, one at the transformer factory and one the standardizing laboratory.

The average of 278 samples tested at the mill and factory agree within 1 per cent, the maximum variation of any one sample between the mill and factory measurements was 3.5 per cent. 100 samples tested at a later date show an agreement within 1/20 of one per cent of the same average loss measured in the two places.

Samples tested in all three laboratories show conclusively that average results are well within 1 per cent.

These comparisons are extremely good in as much as the mill test results quoted are results of single observations; the results given at the other points are, in many cases, the average of several observations.

There is one advantage in quoting results as hysteresis loss, as is done when tests are made on the small set (using 1 lb. sample 10 in.x ½ in.) It has been demonstrated that the eddy current loss is a function of the kind, shape and thickness of material and geometrical construction of the test sample or transformer and is independent of total loss or manner of cutting sample as regards direction of rolling.

The hysteresis loss is a value to which may be added the eddy loss to give total core loss at any desired frequency for any size or shape of test sample or transformer after these eddy losses have been determined by separation tests on a comparatively few representative samples.

As is shown in the paper, this is true for the rings and other samples mentioned. It is also shown by Lloyd and Fisher (U. S. Bureau of Standards reprint 109) and other writers. The writer has found it true for various transformer cores of the same types and material.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 25, 1911.

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TRANSMISSION APPLIED TO IRRIGATION

BY O. H. ENSIGN AND JAMES M. GAYLORD

The subject of transmission applied to irrigation covers a very broad field of electrical, hydraulic and mechanical engineering. It presents problems of finance and agriculture and must also be viewed from the humanitarian standpoint. There are a number of distinct conditions which lead to the use of transmitted power for pumping in connection with irrigation projects. The more important of these conditions are the following:

1. In some cases high lands which can not be reached by the diversion works constructed for a gravity system can be reached by pumping water from the gravity canals into canals feeding such high land areas.

2. The irrigated area may be advantageously extended by pumping from wells, thus drawing on the underground sources and tending to keep the water plane down, this plan being particularly desirable in certain cases, as will be explained farther on in this article.

3. Pumping may also be applied to the drainage of low lands, water being pumped to either irrigation or waste ditches.

In connection with the diversion works, it frequently occurs that a considerable amount of hydraulic power can be advantageously developed, and in such cases this power may be transmitted and applied to any or all the purposes named above. Where hydraulic power cannot be developed, steam or other engines must of course be employed.

This paper will be devoted mainly to the discussion of two hydroelectric transmission systems constructed by the Reclamation Service, one applied to the irrigation of high lands by pumping from gravity canals, and the other applied to the extension of the irrigated area by pumping from the underground sources. The former of these has been nearly completed. In the latter, however, only a small portion of the contemplated development has been finished.

It may not be inappropriate in this discussion to call attention to the advantages of pumping the ground waters of an irrigated area. The advantages of such a plan are, first, to prevent the rise of the ground waters to a point dangerously near the surface and, second, to supplement by means of drawing on the underground supplies the water stored in the reservoir or diverted from the natural flow of the streams.

The rise of the ground waters damages the land in an arid climate by allowing evaporation to take place from the surface or from near the surface of the ground, thus increasing the amount of deleterious salts in the surface soil, gradually causing the land to become alkaline in character and non-productive, hence it is essential that the water plane should not rise beyond a certain limit.

It may generally be considered that the thorough watering for irrigation purposes of a large area of land which heretofore has been drained by the rivers which have flowed through it will tend more or less to cause a rise of the ground waters, hence the importance of this particular phase of irrigation.

In some cases the natural underground drainage may be such that the rise of the water plane will be limited to a reasonable depth below the surface, but there are many examples in the West where this has not been the case and lands which were once unusually productive have been made valueless on account of the rise of the water plane. In some instances it may be necessary to drain this water off and let it waste, because it may carry a percentage of salts that would damage the land, but in the majority of cases it may be pumped from wells into canals and distributed.

Southern California presents a good example of this condition, for practically two-thirds of the water supply for this wonderfully productive area is obtained from underground sources. The water plane in a large section of this area is maintained at least 50 ft. (15 m.) below the surface of the ground, thus giving good drainage and constantly improving the condition of the surface soil. All of this pumped water is used for irrigation.

In all irrigation projects, whether by gravity or pumping, the first thing to be borne in mind is will it pay; that is, can the land stand the charge for the development and the cost of operation of the same. Here the question of climate and the class of products which can be raised upon the soil must be taken into consideration. In some localities a cost of $40 per acre (0.4 hectare) would be a limiting price for the development. In other cases a charge of $100 per acre would not be excessive. The charge for maintenance and operation may vary from $2 to $25 or $30 per acre per annum, the nature of the crop being the controlling feature. It might be mentioned that alfalfa is being grown in Southern California irrigated by water which is pumped from wells, and that orange groves are irrigated by water pumped in some cases as high as 200 feet, both with apparent financial success. On the other hand, to develop water for irrigation in the northern climes, where the season is short, and such crops as alfalfa, grain, potatoes, etc., must be depended upon, the maintenance cost per acre must be kept at a minimum.

MINIDOKA PROJECT

In the central southern part of Idaho, along the Snake River, The United States Reclamation Service has constructed what is known as the Minidoka project. This project comprises 130,000 acres (52,609 hectares) of land, of which, roughly, 70,000 acres (28,328 hectares) are fed by gravity system on the north side of the river, 10,000 acres (4,046 hectares) by gravity on the south side of the river the remaining 50,000 acres (20,234 hectares) on the south side being supplied with water pumped from the south side gravity canal. (See map, Fig. 1.)

The Minidoka dam, designed primarily to divert water into the gravity canals, was constructed during the years 1904, 1905 and 1906. It is a rock-fill dam with concrete core, located near the foot of the rapids in the Snake River. It creates a fall which averages 46 ft. (14 m.) through the various stages of river discharge, and thus offers an excellent opportunity for development of power. In order that the water might be diverted from the main river channel during the construction of this dam, a deep sluicing channel was made through the lava formation on the north side of the river, and in this sluicing channel was constructed the concrete dam shown in Fig. 2. This structure was built, so far as could then be foreseen, without complete power plant designs, so that it could later be used for the development of power. Through the base of this dam are five sluicing gates, and higher up are ten 10-ft. (3-m.) circular openings to be used for the power development.

In February, 1908, instructions were given to proceed with the design and construction of a plant at this point to supply power for pumping water to the high-land area 15 miles (24 km.) distant. This work was immediately undertaken and pushed with all possible speed. On the 8th day of May, 1909, one unit in the power plant and one unit in each of the three pumping stations were started and operated throughout the irrigation season.

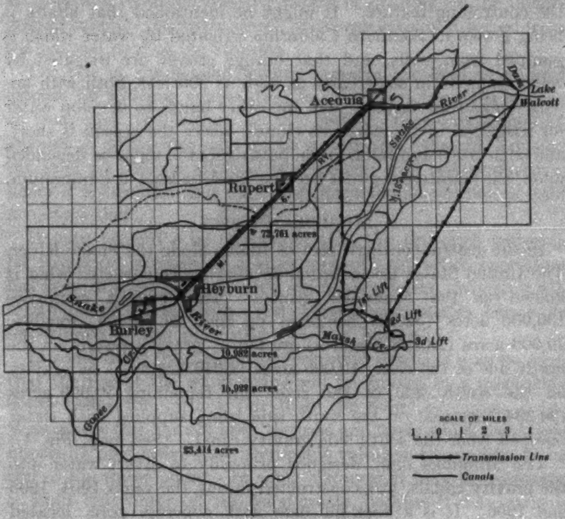
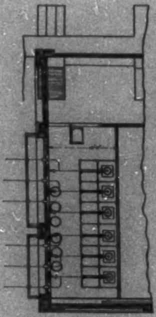

Dam
Lake Walcott
Acequia
Snake River
Rupert
72,761 acres
Heyburn
Snake
Burley
River
1st Lift
2d Lift
3d Lift
Marsh Cr.
Cr.
10,982 acres
16,929 acres
Goose
23,414 acres
SCALE OF MILES
1 0 1 2 3 4
Transmission Line
Canals

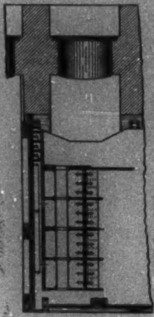
FIG. 1.—Minidoka project, Idaho.

The power plant equipment includes the following:

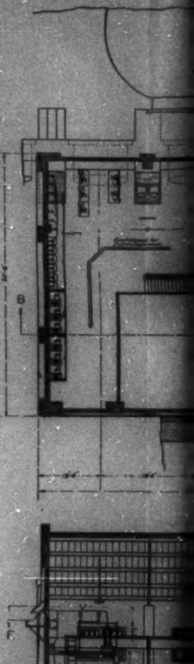
- Five 1400-kilovolt-ampere, three-phase, 60-cycle vertical alternators, each connected to a 2000-h.p. hydraulic turbine.
- Two 120-kw., vertical exciter units, each direct connected to a 180-h.p. hydraulic turbine.
- Five three-phase, air-blast transformers, delivering 33,000-volt current to the high-tension buses.

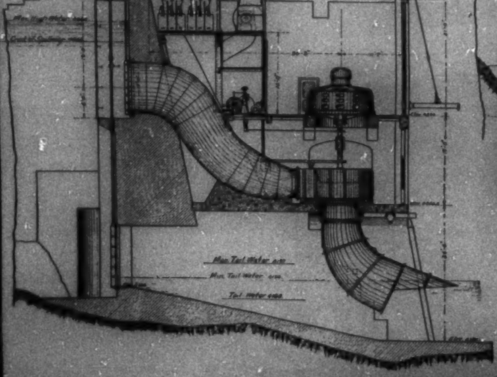


SECTION F-F—LIGHTNING ARRESTER GALLERY.

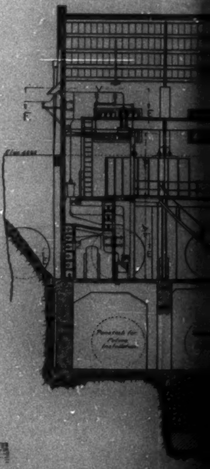


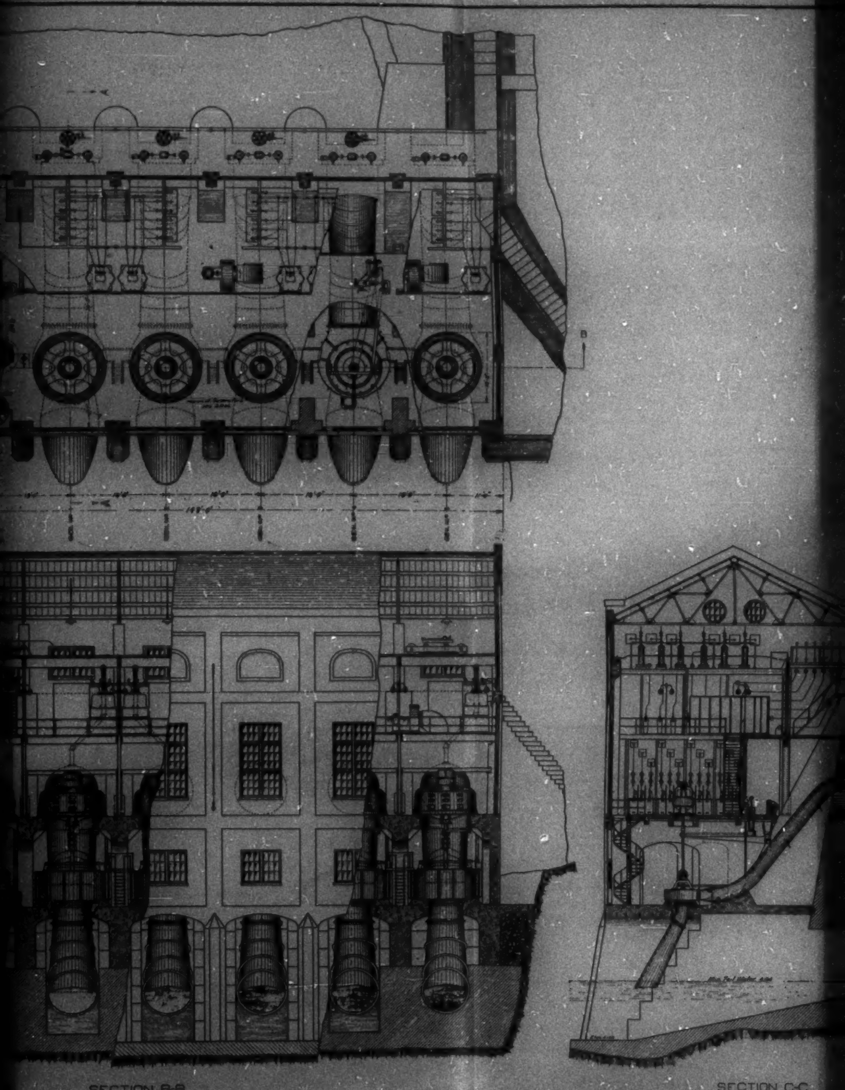
SECTION E-E—THRU OUTGOING LINES SWITCH COMPARTMENTS.




D
D
Max. High Water elev.
Crest of Spillway elev.
Max. Tail Water elev.
Min. Tail Water elev.
Tail Water elev.

SECTION A-A


F
Penstock for Future Installation


B
SECTION B-B
SECTION C-C

arrangement, Minidoka power plant.

The general arrangement of the plant is shown in Fig. 3, and is further illustrated by Figs. 4 to 7.

The turbines are on the lowest floor of the power plant and are carried upon heavy reinforced concrete arches, built up from the bottom of the diversion channel and the buttresses of the dam. The alternators rest upon a reinforced concrete structure and are connected to the turbine shafts by means of clamp couplings. The thrust bearings are located on top of the alternators, which puts the shafts in tension. These are plain collar bearings running in simple oil baths without pressure, and this type of bearing has proven entirely satisfactory. They have given no trouble whatever in two years' operation. The arrangement of the exciter units is identical with that of the main generators, except that in the case of the exciters the thrust bearing is located on top of the turbine.

FIG. 2.—Concrete structure in diversion channel, Minidoka dam.

In order to utilize the waste room resulting from the peculiar construction of the dam and the space occupied by the penstocks, a gallery was constructed the entire length of the building along the lower face of the dam and on this gallery are placed the air-blast transformers and high-tension oil switches. The 33,000-volt bus-bars are carried on insulators above this gallery from the south to the north end of the building, where they enter concrete cells and are led to the line switches located at this end of the building on the generator floor. Below the transformers is a large air duct supplied by two motor-driven fans, and below the air duct on the generator floor all of the governor apparatus is placed. The operating switchboard is at one end of the station and the portion now installed, including the total output panel, faces the machines it controls. It is intended later to extend the present building by adding a wing along the north side of the tailrace, and that portion of the switchboard shown on the drawing for future installation will face this extension. The lightning arresters are located on a special gallery above the switchboard proper.

The hydraulic equipment consists of five 52½-in. (1.33-m.) vertical turbines, arranged in special steel cases which are connected to the dam by means of 10-ft. (3-m.) penstocks, controlled by motor-operated cast iron gates. It was necessary to connect these penstocks and install the gates and trash racks without lowering the water in the lake. The water surface is from 16 to 20 ft. (4.87 to 6.09 m.) above the bottom of these gates, and the problem of installation was solved by designing a special wooden cofferdam, hinged at the top of the dam and which could be swung down against the up-stream face of the structure by filling with gravel pockets provided on the back of the coffer-dam. With the cofferdam in place the space immediately in front of the penstock openings was unwatered by cutting through the stop logs in the 10-ft. (3-m.) opening. By this means the installation of gates and trash racks was successfully and cheaply accomplished.

FIG. 4.—Exterior, Minidoka power house.

The governors for the main turbines are all supplied from a central oil-pressure system, consisting of two gear pumps, driven by 40 h.p. direct-current motors, suitable pressure tanks and brass-pipe distributing lines. No receivers or vacuum tanks are used, the oil from the governors being returned to an open tank in order to allow the oil to settle and any entrained gases to escape. Governor heads are provided with means of control from the switchboard, this control being sufficiently close for synchronizing and dividing the load between units, and if need be the turbines can be started and stopped by the switchboard operator.

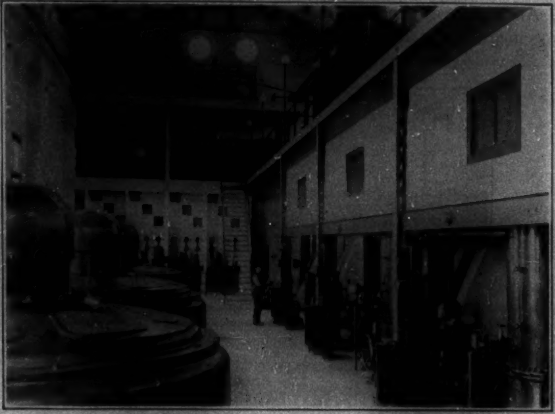


FIG. 5.—Interior, Minidoka power house.

The turbines were designed to meet the following operating conditions: Effective head 46 ft. (14 m.); maximum power 2000 h.p.; speed 200 rev. per min. The maximum efficiency guaranteed by the makers is 81.5 per cent. The guaranteed average efficiency between half and full gate is 77 per cent.

The electrical apparatus is connected on the unit system to duplicate 33,000-volt bus bars. All synchronizing is done at 33,000 volts, oil switches being provided on the high-tension side of the transformers only. These switches are located adjacent to the transformers and are operated by remote control.

Provision has been made for two transmission lines, either of which can be operated from either bus.

The operating characteristics of the power plant apparatus are as follows:

Alternator, 1400 kilovolt-amperes, 2300 volts, three phase, 60 cycles, 200 rev. per min.; regulation at 100 per cent power factor, 8 per cent; efficiency at full load, 96 per cent; temperature rise at full load, 40 deg.

Transformers, 1400 kilovolt-amperes, low voltage 2300, high voltage 33,000 *Y*. Regulation at 100 per cent power factor, 0.9 per cent; temperature rise at full load, 40 deg.; efficiency at full load, 98.4 per cent.

All of the apparatus has exceeded the requirements of the specifications in actual performance.

FIG. 6.—Tail race excavation, Minidoka power house.

The transmission line, consisting of a single circuit of No. 3 and No. 5 B. & S. copper, carried on wooden poles, is 22 miles (35.4 km.) in length and crosses the Snake River in an 1150-ft. (350-m.) span of six-strand, 83,000-cir. mil copper cable at a point 11 miles (3.3 m.) below the power plant. A second similar line is being constructed on the south side of the river, using No. 5 wire, and the two lines will be connected as a loop system through the stations and to the towns on the project which are being supplied with light and power.

There are three pumping stations, each having a lift of 31 ft. (9.4 m.). No. 1 contains 5 pumps, four of 125 second-feet capacity and one of 75 second-feet capacity; No. 2 four pumps, each of 125 second-feet capacity; and No. 3 three pumps, two

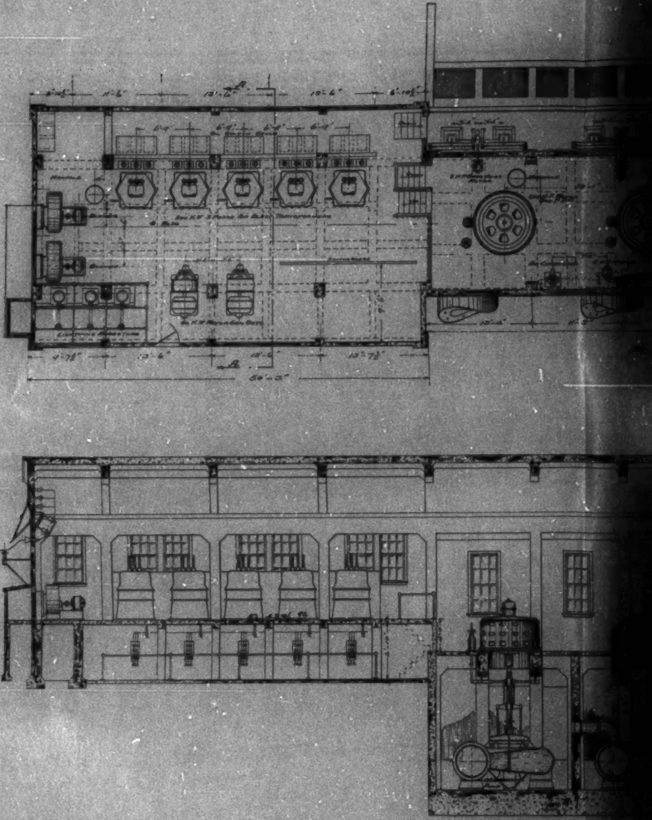
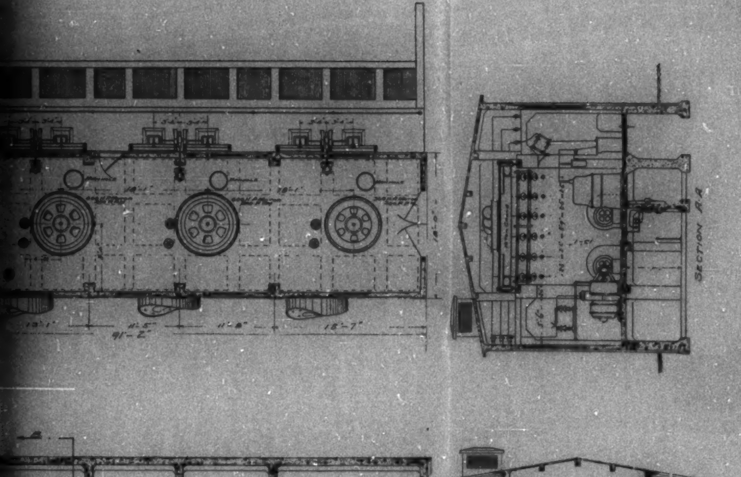

A
4'-7½"
13'-6"
15'-6"
13'-7½"
80'-3"
Lightning Arresters

FIG. 8.—P


14'-1"
16'-1"
18'-0"
13'-1"
11'-5"
11'-8"
18'-7"
91'-2"
Section A-A
14'-0"
17'-1"
Section B-B
Center Line

o. 1, Minidoka project.

[Ensign p. 811]

of 125 second-feet and one of 75 second-feet capacity. The general arrangement of these pumping stations is shown in Fig. 8.

The problem in a system of this kind is to supply at as high an efficiency as practicable, taking into consideration operating conditions, first cost and maintenance, water in variable quantities with the least liability of shut-down and the least possible operating expense. Bearing this in mind, the choice of design of pumping station and especially the arrangement of the pumping units requires no small amount of study. The ordinary horizontal pump with the necessary foot valves would have made an expensive and awkward plant, and such an arrangement would have required a much larger amount of floor space than that occupied by the vertical units which were finally decided upon. The foot valves alone would have introduced a serious loss of head by offering considerable friction, and the control of the discharge of the water by means of gate valves would have involved an expensive installation and a constant source of annoyance in operation. The idea of controlling this pump by means of a cylinder gate, similar to those used in water turbines, resulting from a careful study of the problem, was carried out

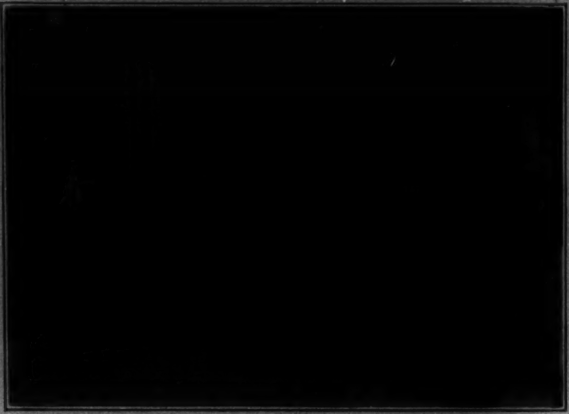


FIG. 7.—Oil pump and governor, Minidoka power house.

with very satisfactory results. By means of this gate the flow of water in the canals is under close control by the operator in the pumping station.

The pumps are installed in separate compartments and are direct connected to synchronous motors located directly above them and supported by a heavily reinforced concrete structure. As in the case of the generators at the power house, the weight of the rotating element is carried by thrust bearings located on top of the motors. In this case, however, the bearing is of the roller type, this style of bearing having been adopted on account of the necessity of reducing friction to a minimum in starting the synchronous motors.

FIG. 9.—Pumping station No. 1, Minidoka project.

FIG. 10.—Pumping station No. 2, Minidoka project.

Motor-operated steel plate sliding gates are used to admit water from the forebay to the pump pits, two gates being provided for each pit. Provision has been made for pumping out the pits in order that the synchronous motors may be started without load other than friction and windage of the rotating parts. For this purpose an auxiliary six-inch (15.24-cm.) centrifugal pump was provided and arranged so that its suction could be connected to any pit and the water entirely removed before the motor is started.

FIG. 11.—Interior pumping station No. 1, Minidoka project

FIG. 12.—Interior Pumping station No. 2 Minidoka project

When the plant was first designed, it was thought inadvisable to adopt an arrangement by which the pumping units could be started in quick succession, on account of the danger of the sudden rush of water down the canal injuring the banks. The auxiliary pump, therefore, is of only sufficient capacity to permit starting of pumps at intervals of 20 to 30 minutes. Two years' operation has shown this to be an unnecessary precaution, and by means of a specially designed starting valve each pump is now arranged so that it can empty its own pit while the motor is running on the compensator in starting. As soon as the pit is emptied the motor approaches synchronous speed and the field is excited. This arrangement has worked out very satisfactorily, and by its use a pump can be started up and put into full operation inside of two minutes.

Each pump has but one guide bearing, a long sleeve with a stuffing box at the top, and near the top of the sleeve the bearing is supplied with a semi-hard oil having the consistency of vaseline, forced in by a special motor-driven pump for each individual bearing. Lubricating in this manner forces the lubricant downward and excludes water from the bearing and any possible grit which may be in the water. In two years' time no rust or wear is shown on these bearings, the shaft being as bright as when it came from the factory.

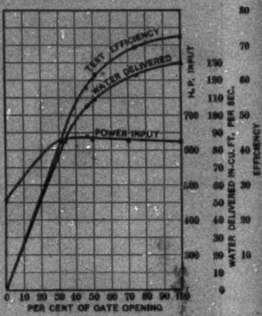


Fig. 13.—Test of 125-ft.-per-sec. centrifugal pump.

Curves giving the characteristics of the pump as to efficiency, power and gate openings are shown in Fig. 13.

The upper end of the 5½-ft. (1.67-m.) concrete force mains leading from the pumps is closed by a check valve, to prevent water from running back to the pump in case of a shut-down. This valve is made up of ¼-in. (6.35 mm.) boiler plate slightly bumped, hinged from the top of the head wall and seating against rubber packing set in a cast iron ring.

The 600-h.p. motors for driving the 125-second-foot pumps are of the self-starting synchronous type, operating at 300 rev. per min. and receiving 60-cycle, three-phase current at 2200 volts.

When operating as generators the characteristics are as follows:

Efficiency at full load, 100 per cent power factor, 94 per cent;
Regulation at 100 per cent power factor, 8 per cent;
Temperature rise at full load, 40 deg.

The motors for operating the smaller pumps are similar except that they have a capacity of 360 h.p. and the following operating characteristics;

Efficiency at full load, 100 per cent power factor, 94 per cent;
Regulation at 100 per cent power factor, 8 per cent;
Temperature rise at full load, 40 deg.

The rotors are provided with squirrel-cage windings, to permit starting as induction motors, receiving for this purpose current at low voltage from compensators. The compensator voltage is so adjusted that the starting current drawn from the line does not exceed normal full load operating current of the motor, and by careful manipulation the motor can be brought into step with the line without exceeding this. It has been found that this can be most easily accomplished by exciting the fields while the motor is running at low voltage on the compensator and then throwing over to full voltage with the machine running steadily at synchronous speed.

FIG. 14.—Switchboard pumping station No. 2, Minidoka project.

The step-down transformers are of the three-phase, air-blast type, receiving 30,000-volt current through oil circuit breakers from the high-tension bus and delivering the 2,200-volt current through disconnecting switches and expulsion fuses to the low-tension bus.

The transformer characteristics are as follows:

Efficiency at full load, 100 per cent power factor, 98 per cent;
Regulation at 100 per cent power factor, 1.1 per cent;
Temperature rise at full load, 40 deg.

In pumping station No. 2 are installed the transformers necessary for station No. 3. The distance between stations 1 and 2 is 1½ miles (2.4 km.), and between stations 2 and 3 three-quarters of a mile (1.2 km.), the highest voltage carried to the latter station being 2,200.

The exciters and blowers for the transformers are driven by induction motors and a motor-driven air compressor has been provided for cleansing the apparatus in each station. Lightning protection is provided in the form of electrolytic arresters placed inside the building.

FIG. 15.—Check valves at head of discharge pipes. Pumping station No. 2, Minidoka project.

All the switching apparatus in the pumping stations is operated by distant mechanical control. A single high-tension bus has been provided, but provision has been made by means of disconnecting switches for receiving power from either or both transmission lines.

The power house and substation buildings up to the motor and generator floor were built during the winter between the middle of November, 1908 and the first of February, 1909, and during this time the weather was very cold, reaching to as low as 15 deg. below zero. Considerable rock excavation was necessary at pumping station No. 2, and at the tail race for the power plant, and the concrete work on all of the structures had to be protected from freezing until set by means of artificial heat.

The apparatus, consisting of one unit in each station, was started in the spring of 1909 in temporary wooden structures covering the motor and generator floors; around these structures permanent buildings were finished during the summer. During the winter of 1909–1910 additional units were installed for the operating season. At the present time two additional units are being installed in the generating stations and two pumps in the pumping stations and during the winter of 1911-1912 three more pumps will be installed.

FIG. 16.—Canal above pumping station No. 1, showing pumped water, Minidoka project.

FIG. 17.—Pumping station No. 3, Minidoka project.

The following table of costs, when considered in connection with the strenuous conditions under which these plants were constructed, may be of interest. The figures given in the table do not include the cost of operators' quarters and road making. These items have been omitted, since they are so greatly dependent upon local conditions. The erection costs, however, include several items such as the cost of making preliminary tests of the hydraulic apparatus, the cost of temporary buildings for housing machinery during the time the permanent buildings were under construction and other items made necessary by the severe conditions under which the plants were constructed.

TABLE I

CONSTRUCTION COST OF MINIDOKA POWER AND PUMPING SYSTEM

	Power plant	Pumping station No. 1	Pumping station No. 2	Pumping station No. 3	Transmission line	Total
Capacity	6,500 kw.	2,500 kw.	3,000 kw.	1,300 kw.	6,500 kw.	6,500 kw.
Building	$80,200	$34,500	$40,300	$19,200	—	$174,200
Machinery	167,600	78,800	73,600	32,500	—	352,500
Freight and hauling	25,100	11,800	10,600	6,100	—	53,600
Erection	62,300	18,200	16,800	8,600	—	105,900
Engineering and incidentals	13,600	5,600	5,300	2,800	—	27,300
Tail race	56,600	—	—	—	—	56,600
Pressure pipes	—	19,000	14,000	16,600	—	49,600
Double transmission line	—	—	—	—	35,000	35,000
Total	$405,400	$167,900	$160,600	$85,800	$35,000	$854,700
Unit cost	$63.00	$67.00	$53.00	$66.00	$5.40	$132.00

A large portion of the riveting of the turbine cases, penstocks and draft tubes was done in the field. In fact, the penstocks and draft tubes were completely assembled at the plant.

It may also be noted that the cost per kilowatt of station No. 2 is based on its transformer capacity of 3,000 kilowatts, while the unit cost at station No. 3 is based on its motor capacity.

In table II is shown the estimated operating cost, based on the actual cost of operation during the season of 1910, of that portion of the equipment then installed. There are two operators on each shift at the power house and there will be but one operator on each shift at each of the pumping stations. The cost of repairs during the season of 1910 was so ridiculously low that the figures given in the table are greatly in excess of the actual cost of repairs last year. This also applies to superintendence and general expense. Five per cent per annum depreciation has been allowed on the power installations, including buildings, and 10 per cent per annum on the transmission lines. No interest charge appears, since funds for the construction of all reclamation projects are, in reality, loaned by the United States to the settlers without interest.

TABLE II

ESTIMATED MONTHLY OPERATING COSTS OF MINIDOKA PUMPING SYSTEM BASED ON ACTUAL COST DURING SEASON OF 1910 EXCLUSIVE OF DITCH TENDING

	Power plant	Pumping station No. 1	Pumping station No. 2	Pumping station No. 3	Transmission line	Total
Capacity	6,500 kw.	575 sec. ft.	500 sec. ft.	325 sec. ft.	6,500 kw.	—
Labor	$700	$300	$300	$300	$100	$1,700
Supplies	150	30	30	15	5	230
Repairs	75	20	20	10	10	135
Superintendence and general expense	400	200	200	150	40	990
Depreciation	1,460	670	670	350	300	3,450
Total	$2,785	$1,220	$1,220	$825	$455	$6,505
Acre feet pumped	—	25,000	20,000	15,000	—	—
Acre feet pumped 1 ft. high	—	750,000	600,000	450,000	—	1,800,000
Kw-hr	3,600,000	1,500,000	1,200,000	900,000	—	3,600,000
Cost per acre ft. 1 ft. high	0.154 ct.	0.163 ct.	0.203 ct.	0.183 ct.	—	0.362 ct.
Cost per kw-hr	0.077 ct.	—	—	—	—	0.18 ct.
Cost per acre per season	—	—	—	—	—	78 ct.

Depreciation at 5 per cent per annum on complete power installation, 10 per cent on line.

Estimates for the six months of the irrigating season assuming that the winter operating expenses are covered by the sale of power.

Allows three acre-feet per acre during season over 50,000 acres.

Average lift 73 feet.

The figures giving the acre-feet pumped by each station were arrived at by comparison of the installed capacity and the acre-feet pumped during the season of 1910, with the ultimate capacity of the various pumping stations and it is found that the figures thus obtained check very closely with the amount of water estimated to be necessary for the successful raising of crops on these lands; namely, three acre-feet per acre per season. The acre-feet pumped one foot high was found for each station by multiplying the total acre-feet for that station by the approximate net lift, namely, 30 ft. The results of last season's run showed that the kilowatt-hours generated at the power plant were almost exactly double the acre-feet pumped one foot high by the pumping stations; and since one kilowatt-hour is equal to 1.01 acre-feet one foot high, this would indicate a working efficiency from power plant to water delivered in the upper canals of approximately 50 per cent. This actual working efficiency should be compared with the following table of full load efficiencies, starting with the water behind the dam and working through the system to the water delivered in the upper canals. The cost of operation per acre-foot pumped one foot high given for the various pumping stations might be taken to represent what a company would expect to pay for operating expenses, exclusive of the cost of power in a pumping station of this character.

TABLE III
FULL LOAD EFFICIENCIES

	Efficiency	Net efficiency from water behind the dam
Turbines	81.5 per cent	81.5 per cent
Generators	96.0 "	78.2 "
Step-up transformers	98.4 "	77.0 "
Transmission line	90.0 "	69.3 "
Step-down transformer	98.0 "	67.9 "
Motors	94.0 "	63.8 "
Pumps	72.5 "	46.3 "

In the table of operating cost it has been estimated that the entire winter operating expenses, including fixed charges, will be covered by the sale of power and that the land under the pumping system will not be charged with any standby expenses for the winter season. In such a system as this, where a large amount of power is required during the summer irrigating season, and none during the winter season, the development of a winter load is very desirable, and with this in view, the transmission lines have been extended to the towns of the Minidoka Project and power is there sold for commercial purposes. Extremely low rates are offered for electric heating and the use of large amounts of power for all purposes during the winter is encouraged in every possible way. By furnishing power at very low rates, especially during the winter months, the annual operating and maintenance charges against the pumping system are reduced and the settlers on the project, who have paid for this work, have the benefit of cheap light, power and electric heat.

SALT RIVER PROJECT

Transmission applied to irrigation on the Salt River Project is an entirely different problem from that on the Minidoka Project. On the Minidoka Project the only method by which water could be obtained for 50,000 acres of land was through the medium of the pumping system. On the Salt River Project a storage reservoir, diversion works and canals are constructed, prepared to irrigate about 260,000 acres (105,218 hectares) of land by gravity and pumps. The pumping system will serve two purposes; one is to prevent the rise of the ground waters to a point dangerously near the surface, and the other is to supplement by the means of drawing on the underground supply, the water stored in the reservoir and delivered by the natural flow of the streams.

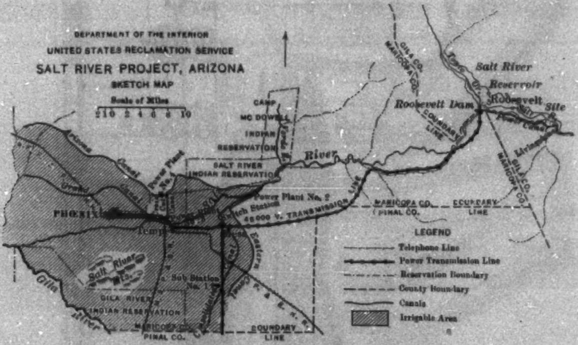

DEPARTMENT OF THE INTERIOR
UNITED STATES RECLAMATION SERVICE
SALT RIVER PROJECT, ARIZONA
SKETCH MAP
Scale of Miles
2 1 0 2 4 6 8 10
CAMP
MC DOWELL
INDIAN
RESERVATION
SALT RIVER
INDIAN RESERVATION
GILA CO.
MARICOPA CO.
Salt River
Reservoir
Roosevelt Dam
Roosevelt
Site
Power Canal
BOUNDARY LINE
Livingston
GILA CO.
MARICOPA CO.
River
Power Plant No. 1
Power Plant No. 2
Switch Station
45000 V. TRANSMISSION LINE
PHŒNIX
Tempe
Mesa
Grand Canal
Arizona Canal
Eastern Canal
Sub Station No. 1
Salt River Mts.
GILA RIVER
INDIAN RESERVATION
MARICOPA CO.
PINAL CO.
BOUNDARY LINE
Gila River
LEGEND
Telephone Line
Power Transmission Line
Reservation Boundary
County Boundary
Canals
Irrigable Area

Fig. 18.—Map of Salt River project.

The power development at the Roosevelt dam consists of two separate hydraulic developments, one from a power canal con-

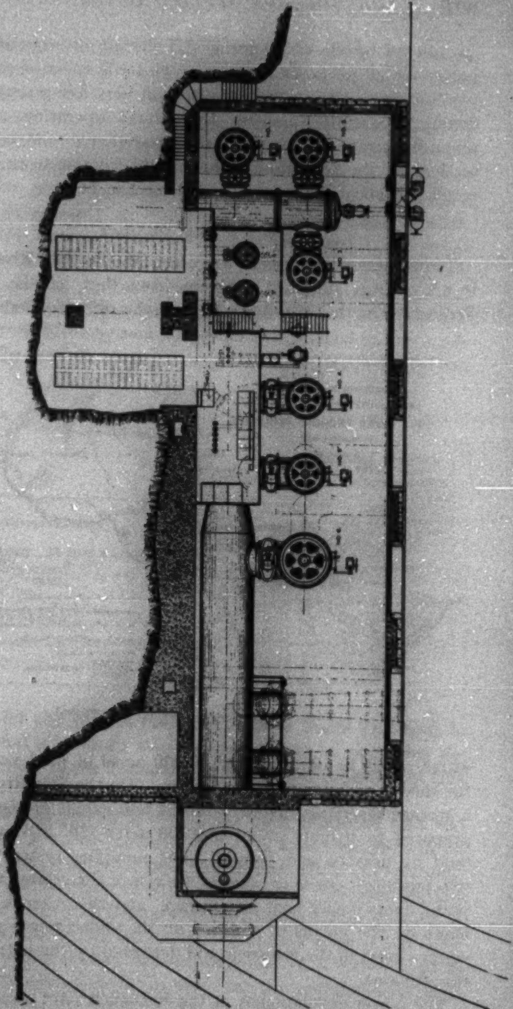


FIG. 19.—General plan of power house, Salt River project

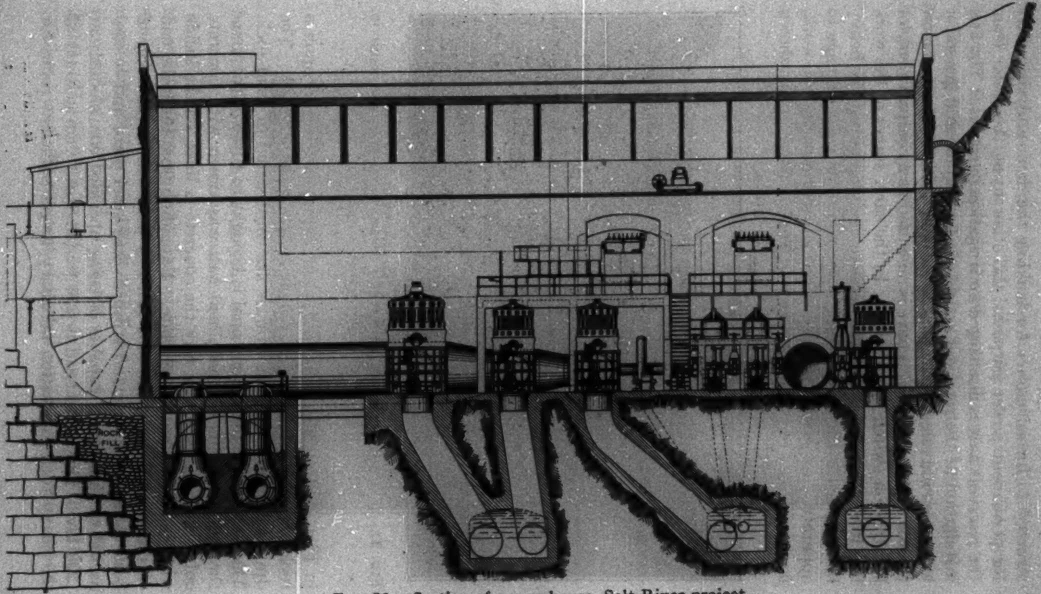


FIG. 20.—Section of power house, Salt River project.

structed to furnish power for building the dam, and ultimately for permanent power purposes; the other using the water from the reservoir as it is discharged for irrigation purposes. The first installation at the reservoir consisted of a turbine and generator in a cave excavated in the face of the cliff, a short distance below the toe of the dam. This cave is now used as a compartment for low-tension switch installation. In the early stages of the work this form of development was necessary on account of the heavy blasting in the vicinity and the consequent danger of damage to apparatus less securely housed. Early in the construction work, however, plans were developed for a complete power plant, shown in Figs. 19 and 20. The power plant was constructed upon a rock foundation formed by excavation of the canyon side. The draft tubes and tail race tunnels are constructed in solid rock. The water from the power canal is brought to three of the units through an incline tunnel, lined half way down with concrete only, the balance of the way the concrete is lined on the inside with $\frac{5}{16}$-in. (7.9-mm.) steel plate. Extending from the lower end of the tunnel the seven-foot (2.1-m.) penstock is made up of $\frac{5}{8}$-in. (15.8-mm.) butt and strap riveted steel plate and is connected to three units capable of being operated continuously at 1200 kw. The static head is 226 ft. (68.8 m.) On account of the heavy rock excavation necessary to get sufficient room for

FIG. 21.—Roosevelt dam showing power house and transformer house in foreground.

the building, economy of space was an important consideration in the design of the plant. This led to the selection of the vertical type of generating unit shown in the illustrations.

The other development is a 10-ft. (3-m.) penstock through the dam, controlled with a large cylinder gate just outside the power house. To this penstock will be connected three units, one of them of 2000-kw. and the other of 1200-kw. capacity. The operating head for which these turbines are designed to give the maximum efficiency is 160 ft. (48.7 m.), and it is expected that they will be controlled to operate at heads ranging from 90 to 220 ft. (27.4 to 67 m.). The reservoir contains above the 110-ft. (33.5-m.) level, 90 per cent of its full capacity. It may, there-

FIG. 22.—Interior, Roosevelt power house, before completion, showing vertical turbines and generators.

fore, be seen that when the reservoir gets below 160 ft. (48.7 m.) while the power of the wheels will fall off greatly, the total amount of energy that is available in the reservoir is not very great.

The generating units operate at 500 rev. per min., producing three-phase, 25-cycle, 2300-volt current. The operating characteristics of these generators are:

Efficiency at full load and 100 per cent power factor, 95 per cent;
Regulation at 100 per cent power factor, 5 per cent;
Temperature rise at full load, 35 deg.

There is a double bus bar switchboard with selector switches for both transformers and generators. These switches are located in the power house and are controlled by a benchboard. The transformers and high-tension switches are located in a separate building, about 600 ft. (182.8 m.) from the power plant. The transformers rest on large castors and are in fire-proof compartments, each three-phase group being isolated by concrete barrier walls. Switches and bus bars are all enclosed in concrete cells. The transformers have a nominal capacity of 350 kilovolt-amperes, but have shown such good regulation and low heating characteristics that they may be operated continuously at nearly double this capacity without exceeding the temperature limits of the Standardization Rules. There are six groups of these transformers, transforming from 2,300 volts delta to 45,000 volts Y, the voltage of the transmission line.

The transmission line consists of six 83,000 circular-mil, six-wire, hard drawn copper strands, supported on 14-in. (35.5-cm.) insulators having a flash-over test of 165,000 volts dry. The line is supported on steel towers with the lowest wire at an average elevation of 30 ft. (9.1 m.) from the ground in the mountains, and a limiting distance of 30 ft. (9.1 m.) from the lowest wire to the ground in the valley. The towers average a distance of 360 ft. (109.7 m.) apart in the mountains, on account of rough country, and 400 ft. (121.9 m.) apart in the valley. This line is 65 miles (104.6 km.) long, reaching to Phoenix, Ariz., the largest town on the project. A branch line taps off from a four-way switching station 40 miles (64.3 km.) from the power house, near the town of Mesa and runs south 20 miles (32.1 km.) terminating in a substation at the Pima Indian Reservation. There is also, about 10 miles (16 km.) south of the main line, another substation for general irrigation pumping. It is contemplated that in the future practically all the power of this plant will be used for irrigation purposes, although at the present time it is supplying the local distributing company in the city of Phoenix with power under a modification of an old contract, in effect before the Reclamation Service commenced work. After the line reaches the cultivated district, the tripartite form of steel pole is used instead of steel towers, on account of the ground space that was saved by such use. Thirty miles (48.2 km.) of this line was exceedingly difficult to construct. In some places the wire had to be drawn through by cables for nearly three miles (4.8 km.), as it was inaccessible by the road. The line was constructed by pulling the wire under tension by means of a steel hauling line over sheaves placed on the cross arm. The cost of 65 miles (104.6 km.) of two-circuit line was $4,400 per mile (1.6 km.).

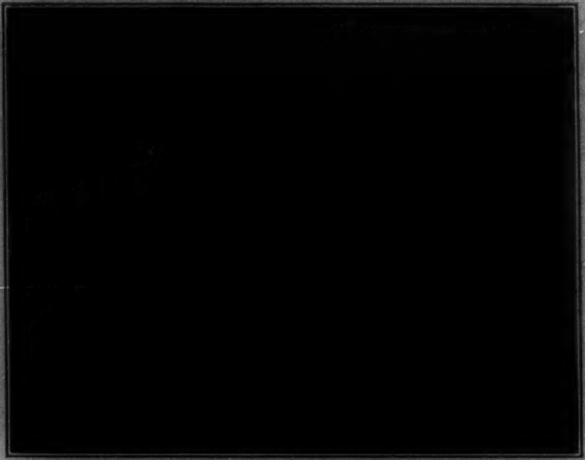


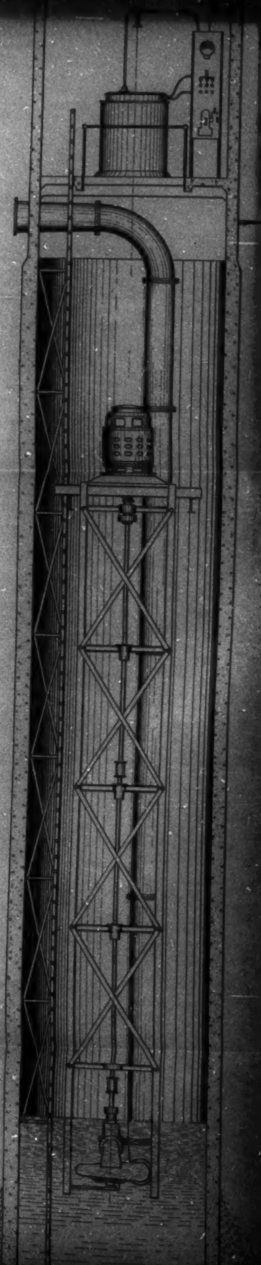
FIG. 23.—Switchboard, Roosevelt power house.

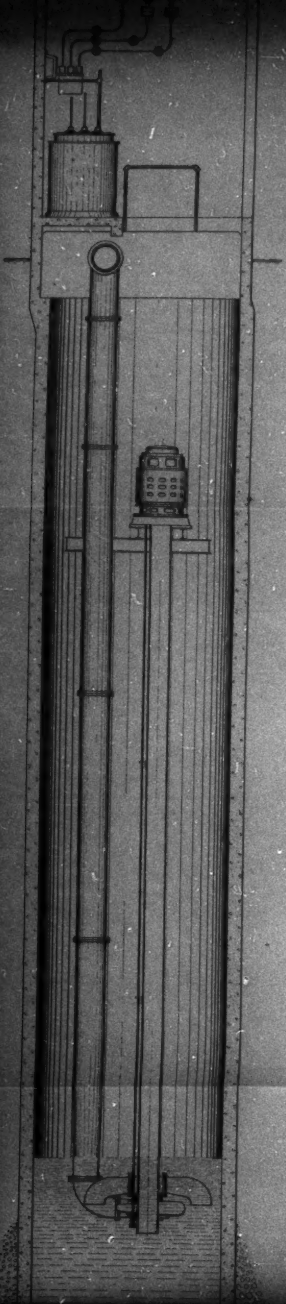
The main transmission line of this system has given absolutely no trouble since the day it was started from any cause that can be traced to the line itself, that is, failure of insulators, towers or similar causes. Shortly after the line was put into operation, however, it developed that large hawks, which exist in great numbers in the plain adjacent to the cultivated area, covering about 18 miles (28.9 km.) of the main line, caused frequent interruptions by alighting on the towers and short circuiting the wires with their wings. The local superintendent has overcome this by installing on the cross arm a small casting provided with sockets, in which are rods of hard wood projecting upwardly, forming sharp points between the insulators. These are very effective and entirely stopped the trouble. The large birds are extremely careful about injuring their wings or themselves in lighting near any such device. The same thing occurred on the branch line recently constructed and this remedy was applied.

The wires are arranged on the towers forming equilateral triangles with 48-in. (1.2-m.) sides.

Fig. 24.—Roosevelt-Phoenix transmission line through the mountains.

One section of the irrigation development by pumping is about completed. This is 12,000 acres (4,856 hectares) of land, to be supplied almost wholly by pumped water, on the Pima Indian Reservation at Sacaton, near the Gila River. There is a flood ditch which will supply water from the Gila when it may be in flood. This is a very erratic stream and can not be depended upon, but its waters are useful in supplying fertilizing qualities to the soil, since it carries a vast amount of silt and dissolved valuable fertilizing material. In the main, however, these 12,000 acres (4,856 hectares) of land will depend upon the pumps. A line of wells was located, about two miles (3.2 km.) from the Gila River, slightly diverging towards the north from the river.





These wells consist of first, a 16-in. (0.4 m.) California well casing driven to a depth of 200 ft. (60.9 m.); a large portion of this depth was found to be of coarse gravel. Around this was sunk a concrete caisson, nine ft. (2.7 m.) in diameter, to a depth of 55 to 60 ft. (16.7 to 18.2 m.). In sinking these caissons a pump having a capacity of 12 second-feet was used, and when a depth was reached which corresponded to the capacity of that pump, to keep the pit dry for excavating purposes, the work was stopped. The top of the caisson was then finished into a small square building for the installation of apparatus. Motor, transformer, pump, etc., were installed as shown in Fig. 26.

FIG. 25.—Roosevelt-Phoenix transmission line in the valley.

The specifications for this pump required a maximum efficiency at five second-feet and 55 ft. (16.7 m.) lift, of 70 per cent, and at 35 ft. (10.6 m.) lift and a correspondingly increased capacity, an efficiency of 63 per cent. In the effort to meet these conditions on a flat top efficiency curve so the motor would not be overloaded at lower heads, the manufacturer obtained a pump giving exceedingly fine results, namely, 80.6 per cent, including the suction elbow and discharge elbow, at 5.5 second-feet and 55 ft. (16.7 m.) lift. The efficiency curves of this pump are shown in Fig. 27.

The pump is a top-suction, vertical shaft pump, carried between galvanized steel channel, forming a frame, which carries a suitable number of cast iron supports and guide bearings. The guide bearings have a pan case on the top to receive hard oil. At the top of the pump shaft is an oil-lubricated thrust bearing in action only as the pump is started. As soon as a small head of water is produced by the pump, a portion of the area of the bottom of the impeller becomes a thrust bearing, which as it starts to lift the impeller, uncovers openings from this thrust area in to the center of the volute, and the opening of these passages balances the pump and stops the impeller in proper alignment with the volute, thus carrying the weight of the impeller and shaft always on a water thrust.

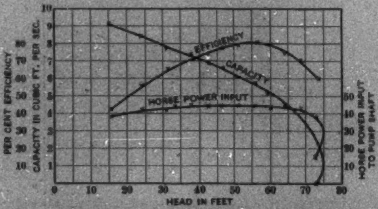


FIG. 27.—Test of 10-in. centrifugal pump, Salt River project.

This water thrust is adjustable by means of a plug attached to a lever and rod leading up to the motor base. A cast iron base for the motor is fastened to the top of the frame by bolts. The top of the vertical shaft is fitted with a jaw coupling. The motor is placed on the cast iron base with the other half of the coupling on the motor matching into the one on the pump shaft and is bolted in this position. The jaw coupling allows vertical movement of the pump shaft as above described. The motor itself has an independent oil-lubricated thrust bearing. Ball bearings are not sufficiently reliable for an installation of this kind, for the breakage of a ball, with the attendant ten miles (16 km.) away, would have serious consequences. Some form of bath bearings is best adapted to this work. In this case the bearing consists of large cast iron collars furnished with a slight oil pressure from a small gear pump located in an oil reservoir holding several gallons of oil and placed at the top of the motor.

The whole mechanism of motor, pump and frame rests on *I*-beams, grouted in the concrete of the caisson. The motor can be unbolted and lifted out and the frame and pump then lifted out independently for examination. The discharge pipe is composed of galvanized riveted iron pipe hung in the caisson in the same way as the motor and frame. The remainder of the electrical equipment consists of 10,000-volt oil switches, a 10,000 to 220-volt, three-phase, self-cooled transformer, provided with taps for starting the motor at half voltage; a double-throw, triple-pole knife switch and an ammeter.

FIG. 28.—One of the Sacaton wells, Salt River project.

Ten of these units in a line ten miles (16 km.) long, and a 750-kilowatt substation, with provision for extension to 1500 kilowatts, are taken care of by two men, one of them an Indian. The pumps run with very little attention. Similar motors on another installation have operated for two years without giving any trouble whatsoever. Similar installations of pumps the writer has known to operate for long periods, with very little attention.

This pump running submerged is always working at its best efficiency. By using a large pump to sink the caisson all the fine material is drawn out of the gravel in the vicinity of the bottom of the caisson and no more sand will be drawn into the well at the reduced capacity of the permanent pump.

Operation to date has given an average minimum discharge of six second-feet for each well, which corresponds to a lift of approximately 50 ft. (15.2 m.) and a pump efficiency of approximately 80 per cent, as will be seen by reference to the test curves of the pump.

The whole pumping system is an exceedingly reliable one. Practically the only attention which seems to have been found necessary to date is the restarting of the pumps after an interruption. It is proposed that this may be finally solved for each group of this kind by starting them all from the substations by means of a compensator in the substation itself connected in the 10,000-volt circuit distributing to these pumping plants.

Fig. 29.—Substation, pumping plant and operators house.

Taking this plant as it stands, solely as a pumping development, without the flood canal, in which case the area supplied would be limited to 10,000 acres (4,046 hectares) instead of 12,000 acres (4,856 hectares) we find some interesting results, as to cost, and it is believed that these results can be improved upon in the next installation of this character, by taking advantage of the experience gained in the sinking of caissons in this installation and probably a saving of 15 to 20 per cent might be made on that portion of the work. The cost of the ten wells and pumping equipment is $105,000, or about $10 an acre (0.4 hectare) for the 10,000 acres (4,046 hectares) which they will supply. Assuming that a power company stands ready to supply the current to the 10,000-volt line in regular commercial work, the following interesting results of cost of irrigation by this method may be deduced.

As shown by the efficiency curve of the pump, the horsepower input to the pump at any head which will probably be maintained in these wells will not exceed 44 h.p. Taking into account shaft losses, piping losses and loss in efficiency of the pump as time goes on, it may be assumed that 50 h.p. applied to the pump is a reasonable figure. The load on the substation calculated from the proven efficiency of apparatus and line would be then 460 kw. supplied to the 10,000-volt line feeding the pumping stations.

Assuming that it is necessary to run this system an average of 200 days a year, 24 hours a day, the installation will consume 2,208,000 kw-hr. To an installation of this size it may be assumed that power can be supplied from a water power plant at not more than 1.5 cents per kw-hr., making a total cost for 10,000 acres (4,046 hectares) of land $34,000 per annum, for power, or $34.00 per acre (0.4 hectare) per annum for the 10,000 acres (4,046 hectares). Taking into consideration the climate existing in this locality and the soil which this water will supply, this is an extremely reasonable irrigation power charge.

The actual method by which the charge for power will be made to this particular pumping circuit, however, is that there will be charged against this section of land a sum representing the cost of the final development of power set aside to supply this pumping system for the Indian Department when it is all completed, and this pumping area will then pay the actual cost of furnishing such power. This will reduce the power cost to about one-third of that estimated above. So far as depreciation, renewals, repairs and attendance is concerned, it without doubt will compare well with any system of its kind heretofore constructed. The wells themselves are of a character which will probably last indefinitely. The equipment is one which it is believed will present a minimum of repairs.

Under the above assumption of operation, there will be 24,000 acre-feet of water lifted an average of 50 ft. (15.2 m.) at a cost for power of $34,000, or at a cost of $1.42 per acre-foot, making $0.0285 the cost per acre-foot one foot high, which is the figure upon which comparison should be made with other installations as to power cost.

In regard to the Salt River Project, it is expected that there may be constructed over 100 pumping plants similar to these described in the Pima Indian Reservation. These will serve the purpose of drainage as well as add to the irrigated area. The power for these plants will be furnished, of course, at cost, as the operation of the pumping system will be a part of the project.

This brief description of these two installations, covering two types illustrating the subject under discussion, represents only a portion of the work of this character which is being carried on by the Reclamation Service. There are many complex and interesting problems connected with the various projects, for which there is no space in this paper.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 25, 1911.

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TRANSMISSION SYSTEMS FROM THE OPERATING STANDPOINT

BY R. J. C. WOOD

REQUIREMENTS

In order that a transmission system may satisfy the operating engineer it should fulfill the following conditions:

1. The requisite amount of power must be transmitted with reasonable voltage regulation.
2. Interruptions must be reduced to a minimum.
3. Flexibility of operation should be assured.
4. Ease of repair is essential.

REGULATION

The voltage to be used is chiefly, if not entirely, determined by economic conditions. It is as easy to operate with 60,000 volts as 15,000; indeed, there seem to be more short circuits and troubles on the lower voltage lines, probably because of the less careful construction used and the lesser absolute insulation margin allowed. We hear from the lines operating above 100,000 volts that they encounter no greater difficulties than do those of lesser potentials.

Up to distances of about 150 miles (241 km.) frequency is not a very vital matter. An increase in voltage will offset the difference in regulation between 25 and 50 or 60 cycles. This factor will be decided by the relative importance of the classes of load demanding either high or low periodicity, so as to make the total cost a minimum, and the consumers' satisfaction a maximum.

There are various formulas for calculating regulation, and it is not necessary to refer to them in detail, beyond remarking that the conditions surrounding the delivery of power are often somewhat indeterminate. The power factor of the load, for instance, is often not to be foreseen between wide limits. This uncertainty renders abortive any extreme accuracy of method as applied to calculating the line.

It will be immaterial, therefore, when considering moderate distances up to 150 miles (241 km.), whether a formula is used, based upon the capacity being all at the center, part at the ends, or uniformly distributed over the line.

The allowable drop of voltage will depend upon conditions. Where power is transmitted in a block from the point of generation to a center of distribution, the regulation may be as high as 25 per cent. In such a case the voltage drop will probably be limited by the value of the lost power rather than by any operating difficulties.

The nature of the load will also bear upon the allowable voltage fluctuations. A mixed light and power load will demand closer regulation than either class of load by itself. If the service is all power a certain unsteadiness of voltage is allowable and if it is all light the changes in load will come on in such a manner that the operator can follow them by hand regulation.

When, however, the transmission line is part of an interconnected network and may have to transmit in either direction, then the regulation must be low in order to keep within the range of the regulating devices used in substations. If, for instance, a hydroelectric and a steam plant are at opposite ends of the line and there are numerous substations between the two, the flow of power may be either way.

Most probably the important center of distribution will be where the steam plant is located, and the voltage must be kept uniform at this end. The voltage at substations along the line will then vary by an amount equal to double the regulation of the line.

This fluctuation can be entirely eliminated from the distributing circuits by using automatic regulators, but the main transmission line should only have one-half the regulation that would be permissible were it a straight one-way transmission.

In loop or ring systems, fed from both ends, the circuit must be heavy enough to permit of feeding the entire load, all around the loop, from either end. If this is not the case it will be found that when certain sections of line have to be cut out for inspection or repairs, the open end of the loop does not get satisfactory service.

The amount of power that should be carried on a single circuit bears a relation to the total power of the system, the importance of certain loads, and the balance that the management draws between insurance against loss of revenue and prestige, and investment costs.

It will probably be wise in systems of 60,000 volts and above to confine the capacity of each circuit to 100 amperes. Baum has shown that the surge voltage, due to sudden interruption, is equal to 200 times the amperes, so that in the above case there would be a rise of 40,000 volts when a circuit breaker went out, supposing it to be open at double normal current. This would give a total voltage of 100,000 when superimposed upon a 60,000-volt line. Line and transformer insulation would stand this momentarily.

In order to deliver uniform voltage to the consumer, a variety of automatic and non-automatic devices are in use. It is questionable whether automatic regulation is desirable at the generating station, unless a type of regulator is used that will discriminate between the drop of voltage, due to increasing load, the drop occasioned by extreme overload, and that due to short circuit.

There are these three conditions to be met. Regulation for variation of load is comparatively simple, but when, due to troubles on the line, certain generating plants get left with more than their share of the load, we need a regulator that will discriminate and lower the voltage to a point where the generators will carry a safe current. Again, if a dead short circuit occurs on the line, the regulator must automatically lower the voltage as much as possible so that the arc may break; it should also, as soon as the line clears up, proceed to slowly build up the voltage to normal. It is too much, perhaps, to ask all this of an inanimate device, besides which it might deprive the switchboard operator of his job.

If synchronous apparatus is in use at the receiving end of the line, an automatic regulator controlling its field is quite feasible and should give excellent results. It entails, however, the fixed charges upon a considerable investment and certain operating expenses. Distributing feeders from substations along the line can be automatically regulated by the various types of induction regulators.

RELIABILITY

Second only to the ability to transmit with reasonable voltage drop is freedom from interruption. To insure continuous operation we must have first class mechanical construction in line and substations. In designing the line we may take the worst climatic conditions on record over at least 30 years and then allow a factor of safety of 2½. This would give a limiting unit tensile stress of 22,000 lb. for copper and steel, and 10,000 lb. for aluminum. Compressive stresses in towers to be reduced by column formulas. The tower should in any case be strong enough to stand the unbalanced stresses produced by the failure of one conductor.

The stress upon pin type insulators may be limited by designing the tie wires to break at the unbalanced stress above mentioned. It is better in case of some catastrophe to a tower, or line, to have the conductors break the ties, then to pull over a succession of towers. To attempt to design a tower that will stand the total breaking stress of all the conductors, leads to economic impossibilities. The transmission should preferably be on a private right of way which should be cleared of trees and brush.

With sufficient spacing of conductors from each other and from the tower structure itself, and with insulators tested to 3½ times the voltage to neutral for grounded Y, and 3½ times line voltage for ungrounded delta systems, there should be no interruptions except those caused by lightning or malicious interference.

The requisite clearance between conductors and tower structure is sometimes underestimated; in certain parts of the country large birds will roost upon the tower. If the insulator is of the pin type they consider it a most excellent device to get under. All goes well until about 4 a.m. in summer time, when the bird wakes up, stretches, and grounds the line. The suspension insulator should be free from this trouble, provided there is enough space between the conductor and the cross arm below it.

To minimize lightning troubles all kinds of arresters have been used as well as ground wires. Ground wires seem to do no harm and in many cases have without doubt prevented trouble. They give an added stiffness to the line mechanically, and are a wise precaution to install in sections habitually subject to storms. So far no arrester is perfect, most or all of them will burn up at times, even the electrolytic type is at times untrustworthy upon delta-connected high-potential systems. The only consolation the operator derives, when his arresters burn up, is the thought that perhaps they saved something more valuable. The most robust type is the horn gap, it needs lots of space to accommodate the power arc that follows a discharge, and it usually shuts the system down when it goes off, but other types sometimes do the same.

It may become necessary to put in, say, electrolytic arresters to take care of the surges, due to switching and minor climatic disturbances, and then protect these arresters with horn gaps, if this be possible, to take the irresistible discharges from heavy lightning, which would cause temporary interruption in any case. When lightning causes a disturbance on the line, the surge will usually not travel far, but will break over an insulator, the arc formed will in many cases break the insulator, due to the intense heat. Ring guards at top and bottom of the insulator have given excellent protection to the insulator, by carrying the arc away from its immediate neighborhood.

The choice of supporting structures will generally lie between steel towers and steel or concrete poles. From some preliminary estimates that have been made it would appear that reinforced concrete poles for long span work will be extremely costly.

Where the districts fed from the line are scattered over considerable territory the transmission will have to be laid out either on a radial or loop system. The loop or ring system has the advantage of giving each substation a source of supply over entirely different routes, which are not both liable to be out of commission at the same time.

If the loop is double circuited throughout, the substations may be divided between the two circuits. Normally, the loop will be open at about its center, being fed from both ends. In case of trouble the circuit breakers at the feeding ends will open up and cut out only about one-fourth of the stations connected. These stations will at once switch over to the good line. The opening in the loop will only be closed under emergency conditions.

The radial system necessitates double circuits on all branches if full protection is to be afforded, and for the same insurance against interruption is more costly than the loop arrangement.

As already incidentally mentioned it will be necessary to have relays and circuit breakers installed upon branch circuits so as to isolate trouble. There does not seem to be any reliable way to automatically cut out the faulty line when one of two circuits, in parallel at both ends, becomes short circuited or grounded. We have had some success when generating at both ends of a two-circuit line. With the inverse time type of relays the faulty line has been cut out automatically at both ends in a great many cases. If generating at one end only then both lines will go out. We need very badly a reliable reverse current relay that will operate at zero voltage.

Any growing system will suffer sooner or later from an inadequacy in its switching devices. Switches that operated perfectly when the total generating capacity was small, will fail more and more frequently to handle the short circuit as the total kilowatt capacity increases.

It will be found that there is no room for the larger switches that should replace the original installation. It is almost impossible to have too much space in the switch galleries and bus bar compartments, and economy of space here, while it may have been attractive and looked all right when the plant was young, is all the same a false economy. The lack of a few extra feet between switches might lead to an entirely new lay out being required in a few years. It is becoming the practice to install additional reactances in generator circuits to limit the short circuit current of large systems. It seems a pity to have to do this and spoil the regulation of the machines to the point where auxiliary automatic regulating devices are essential. It is a question whether such immense systems should not be normally cut apart into sections of perhaps 50,000 kw. capacity. This would simplify operation and localize trouble.

Even in smaller systems, normally operating as a unit, it is necessary to have points where they can be instantly cut apart, leaving certain loads on certain generating stations. This is the operator's first move when short circuits occur; to separate the several sections so that the greater part of the system may suffer as short a time as possible. If all important transmission lines were built with at least three circuits then they would be self clearing, using only inverse time relays at both ends. It is, however, often difficult to get the money to build three lines where two will apparently suffice.

Too much complication in providing for all imaginable combinations of switching is to be avoided as defeating its own object, which should be to keep the customer supplied with energy as continuously as possible. When the operator has to stop and figure out what to do next in cases of trouble, precious moments are being lost. To insure prompt operation a good telephone line is a necessity and the money will be well spent in building an independent pole line for its use. A telephone line running upon the same towers with the transmission lines is very likely to be inoperative just when it is most needed.

It is perhaps possible to formulate a set of rules, so that each station in a network knows exactly what to do under all conditions, but a word from the load dispatcher is worth many rules in the book.

REPAIRS

There should be sufficient circuits and switching facilities so that all sections of the line may be cut out for inspection or repairs. It is an added precaution to have ground clips on all line disconnecting switches, so that when a line is killed with the object of working upon it, it is also grounded at both ends.

Long transmission lines should be sectionalized so that is never necessary to cut out more than a fraction of the line at any one time. By having switching stations a convenient distance apart they also serve as resting places for the patrolmen. Circuits should also be so arranged upon the towers or poles that men may work upon it without getting into dangerous proximity to the other circuits which will be alive.

CONCLUSIONS

All the foregoing requirements are summed up in what might be as good a motto for the operating engineer as for the system he operates, namely: capability, reliability, flexibility and repairability.

DISCUSSION ON "TRANSMISSION APPLIED TO IRRIGATION", AND "TRANSMISSION SYSTEMS FROM THE OPERATING STANDPOINT." LOS ANGELES, CAL., APRIL 25, 1911.

A. H. Babcock: Mr. Woods' paper is practical because it is based on real experience. For some years it has been my opinion that if more such experiences were put on record much good would result.

The author states that for distances up to 150 miles it is immaterial whether the capacity is taken as being all at the center, part at the ends, or uniformly distributed. Perhaps he will be willing to give his opinion where the line must be drawn, *i.e.*, what is the limiting distance where one's assumptions should change.

It is also stated that the tower should be designed for the unbalanced strains produced by the failure of any conductor. Is it not usual that when one line fails it takes another with it? It seems to me that it is necessary to go a little further and to provide for simultaneous failure of at least two conductors. Of course the financial conditions of the problem must determine in the end how far such insurance can go.

The author's remarks on switching must strike forcibly those who have been obliged to remodel switching and bus bar structures that have been found inadequate.

C. L. Cory: An interesting point brought out in a paper presented in San Francisco last May by Mr. Hays on the irrigation system developed in the San Joaquin Valley for the Mt. Whitney Power Co. was that in that plant certain economies resulted from not investing too much money in the beginning.

Wooden flumes were found in that particular installation to be quite satisfactory, and wooden pole lines gave good results. In the beginning the load was not heavy; and as the load increased, a reserve steam plant was installed down in the valley; and as an ultimate result the plant was a success. In other words, the duration of time necessary to get a load for this irrigation plant was such that it was not advisable to build a plant at first for all time.

The two plants described by Mr. Ensign and Mr. Gaylord, while for an entirely different class of service indicate that there are some circumstances where the character of work may even in our irrigation problems be permanent. I believe that the authors will agree with me that perhaps there are instances where this excellent construction would hardly be justified in the very beginning, as unquestionably was the case in the early days of the Mt. Whitney Power Company.

But when we see plants designed, laid out, and completely developed in every detail, such as the plant in Idaho and the one on the Salt River, we are impressed with the fact that irrigation and the use of electricity in pumping for irrigation, has come to about the same standard as the transmission plants for metropolitan use for transportation and other purposes. I have had the pleasure of seeing the plant at Salt River, not all completed as described in the paper today, but there are a number of features about that plant that I recall. The tower line from Roosevelt into Mesa and Phoenix is a pleasure to see. There is a separate telephone line put up in a permanent manner—not upon wooden poles but upon inexpensive pipes or straight iron poles, and the entire construction is excellent.

There is one thing in making even a preliminary investigation of the installation of electrical plants for irrigation, which has to be constantly borne in mind. Mr. Ensign, as I remember it, said this morning that the capital charge against the land which would be irrigated from the Idaho plant was about $40 per acre.

Now, ordinarily when we build a large steam generating plant, or a transmission system which is used for transportation purposes, light, heat and domestic use, we do not necessarily have to consider the source of the money to pay for the income on the investment which ultimately takes care of all such charges, as depreciation and operating expenses. When we start to irrigate 200,000 acres of land, such as the Salt River project, including the storage reservoir, Roosevelt Dam, and canal system, and you see this land, as you might have seen it 10 or 15 years ago, you are impressed with the fact that the $40 per acre must come out of the productiveness of the land itself. In other words, it cannot come as an immediate result. The $40 per acre may possibly come in a few years, or it may require a number of years. In general, whether we have a gravity system of irrigation, or a large electrical installation, with the pumping plants and so on, the capital invested, the maintenance charges, cost of operation, and so on, will not be returned as rapidly as in many other installations of large plants. The investment is reasonably safe if the supply of water to be pumped is permanent and of the proper character, but there cannot be that immediate return, nor, I suppose, is it possible as quickly to load up the plant.

There is one point about which I would like to ask in regard to the first paper, and that is the period of the year or the annual load factor, if we might put it that way when electrical power would be used or needed for irrigation. To put it more definitely, I have in mind one location in New Mexico where it would not be necessary to pump water earlier than the latter part of February or the first of March. The summer rains come along in August, and it is only between March 1st and August 1st when the crops are starting that pumping is required. It is an important problem, under some circumstances, as to what we are going to do in irrigation projects with the power that may be generated at another period, or what are we going to do with our transmission plants of the character of the Idaho plant, if it is true that our irrigation is only needed five months out of twelve?

E. F. Scattergood: I wish to commend Mr. Ensign for having presented some cost figures in connection with the projects which he has taken time to describe. I do believe, further, that the time which we spend, as engineers, in writing descriptions of projects, and in reading descriptions written by others, is doubly valuable when accompanied by a statement of the features of construction and operation that have proved good and also of those that have proved unsatisfactory. We do not always hear about the bad ones, as we should and we should always be given the costs.

I remember very well my early experience with the Los Angeles Aqueduct work in planning for power for construction. I looked here and there and probably overlooked, but found very little of any benefit to an engineer wanting to know how much power is required, in a general way in construction work of that character; in what way to apply it and something as to costs. It seems that power is one of a number of such items that are usually allowed for by a sufficient percentage in estimates and paid but little attention while constructing such works resulting in an unnecessarily large total cost. After the first two years of aqueduct work I made careful summaries of the results as to the amounts of power required; the best methods of applying it; its bearing as to economical tunnel and conduit construction; the actual costs of the power system and the power delivered and comparisons with what the costs would have been if supplied by other methods. This was done for my personal use but when completed it was given to the Institute as published last August with the hope that it may be of benefit to others.

More such frank statements as those by Mr. Ensign would mean better team work and much greater accomplishment with an incidental betterment in the standing of the profession and every man in it. I do not see any disadvantage in it. I do believe that sometimes it might do perhaps some little harm, but I do believe there has been more harm done through ignorance of costs on the part of the public, than there ever would have been done through a proper knowledge of costs. There has unquestionably been great harm done, at times, through ignorance as to costs and in far more instances even greater injustice and wrong committed by taking advantage of such ignorance. I would like to know from Mr. Ensign whether or not the department would be free to develop power not needed for pumping purposes, and sell it, in order to make the results of the irrigation project more favorable to the farmer?

Paul M. Downing: In looking over Mr. Wood's paper, I find that his experience along different lines is very much the same as my own. He states that he does not consider any type of automatic regulator as being satisfactory for controlling the voltage at the generating end of a long transmission line.

This is particularly true of a large net work supplied from a number of different sources. On a system of this kind there are a great many conditions coming up which affect the power house regulation. The character of the load may vary through a wide range during the 24 hours. The voltage regulation of one generating station will be dependent not only on the load carried from that station, but on the load carried from every other generating station, etc.

The conditions are entirely different from those obtaining where you have a single generating station and no inter-connected net work of lines.

I cannot agree with him when he states that the first cost of a synchronous condenser is a strong argument against its use. On the contrary, I think that very often it is an economical way of increasing the amount of power which can be delivered over a line.

On any long, high voltage line you almost invariably have a low power factor due to the induction motor load. This, together with the inductive drop in the line, gives poor line regulation. The use of a synchronous condenser enables you to raise the power factor to more nearly unity, but gives a most satisfactory means of regulating the line voltage.

The lightning arrester trouble to which he refers is something I think we have all had more or less experience with. Fortunately here in California there is little use for lightning arresters except in the higher altitudes.

Our greatest trouble, particularly in the Bay Districts, is from poles burning due to leakage over the insulators. Where you have one case of lightning trouble you will have a dozen cases of trouble from poles burning. This condition is generally the worst about the time of the first rains when the insulators are covered with the summer's accumulation of dust before they are washed by the winter's rains, and sometimes even two and three times during the summer and fall, to prevent this burning. After the first heavy rain little if any trouble of this kind is had.

J. A. Lighthipe: One of the points that was brought out by Mr. Wood's paper very strongly is that those who build a power system have no idea of what it will grow to be. The northern part of this State is practically under one system.

In Santa Anna we started with 33,000 volts, and 3000 kilowatts, and we were wondering what we would do with all that power. The whole line is now running in the opposite direction. The section surrounding Redlands is using about 10,000 kilowatts, and it is an open question whether we won't pump a great deal more to that end of the valley before many years.

The whole question of laying out stations and lines is a matter of prophesy. We don't know what we are going to run into in a few years. Fifteen thousand volts seemed to be almost the limit up to a few years ago. The first step to 30,000 simply staggered all the manufacturing companies. I can remember Dr. Bell publishing papers in which he stated that 40,000 was the limit that we could go; and we could not possibly run beyond that. Now 60,000 is a common proposition. It is an open question whether we won't creep up to 100,000 or a 150,000, and we will have to if we increase our distances and areas of distribution.

Ralph Bennett: Mr. Lighthipe has mentioned the increase in voltage in recent years. We have now been operating in the Bay district for some time with 100,000 volts, and we have no more trouble with it than Mr. Downing had with 60,000 volts. In fact most of our trouble has been acquired from the 60,000 volt circuits which we feed.

A question has been raised as to the proper strength of towers. It is true there are times when several wires fail, but it is also true that there are usually additional circuits on the tower wires which will not fail and which will aid it in standing. Our suspension insulators are good for 15,000 lb.

After a flash-over, due to fog on the insulator, or lightning trouble, we can at once resume service. It is not like the old condition with wooden poles and wooden arms, where when we burned the pole head off we had to send a crew out to fix it up.

C. W. Koiner: Messrs. Ensign and Gaylord's paper on Transmission should be of very great interest to all companies operating in the West.

Power for irrigation is now furnished on a great many transmission systems throughout the southwest. It should be profitable for the reason that this load can be taken on the off-peak. The paper is full of valuable detail cost, and it is apparent that a fair price can be received for power.

The construction cost when compared with similar cost of work elsewhere, is very low. This same thing applies to Table 2.

The capital cost allowable per acre for irrigation depends entirely upon what the returns are per acre. It should be remembered that to rehabilitate the old eastern farms and plantations in the South, we are called upon to put back in the soil from $15 to $30 per acre, and sometimes $40. If it costs $40 per acre to irrigate virgin soil in the west, this should not be high, when we compare it with our old eastern farms, and they are beginning to return increased profit on the cost of rehabilitating. It would be interesting to know to what extent power is used for heating from the Idaho plant in the winter.

L. J. Corbett: Mr. Cory raised the question of the length of time that the power was used for irrigation. Up where we are we have even a shorter season than he seems to think is profitable. Some of the contracts I have been instrumental in getting on propositions of that kind from power companies have been as low as three months. One hundred days is the usual irrigation season, and sometimes, for safety, we stretch it from the 15th of May to the 15th of September, making it four months.

A question, which was hardly an electrical one, but more of an irrigation question, that was interesting, was the idea of using the surface waters and preventing them from rising beyond a certain level and reducing them by taking them off and using them elsewhere for irrigation. That was a difficulty in the early days, in the Yakima region, and a great many people used it as an argument against irrigation, saying that it spoiled the land, making it sour, and that after a few years the land was ruined; but with the methods that are being developed now and the studies being made, such damage will be prevented.

Around Spokane there is a very interesting condition. The Spokane Valley is all underlaid with gravel. There are deep gravel beds ranging from 50 to 150 and even 250 feet deep. We have not gone to the bottom of them, but there is a water sheet there that certainly contains more water than the Spokane River, that travels right down through the valley. There is coarse gravel at most places at the water level, but there is such a flow going through that if you drop chips or sawdust on one side of a well, it is but a little time until it goes to the other side in the direction in which the river is flowing. To show what a heavy flow there is I would say that from wells eight feet in diameter, large centrifugal and turbine pumps are pumping as much as 5000 gal. a min. without visibly lowering them. When the pump is first started the water level falls from a foot to a foot and a half, where it remains constant. It pours right in from the sides. It is just like pumping out of a lake. The land the water is applied to is a black gravel soil and there is no danger at all of souring that land. The water is never left on the surface except in some cases in the winter when the ground is frozen and the melting of the snow leaves pools. It is well drained naturally. They are putting in wells there and buying power from the power companies.

In the discussion it was brought up by one of the members that irrigation came on the off-peak period. There are two companies furnishing power there, and one company, which has had a railroad and lighting load offered a special contract at reduced rates, if the irrigators would keep off their peak, which was from five in the evening until 11 o'clock at night; but in this particular place in the valley, tracts were being sold to parties living in and around Spokane, and many of the purchasers were working in Spokane and would come out there in the evening to take care of their suburban homes. Also the evening was considered the best time to irrigate and in this case that contract was refused and a higher rate paid in order to be at liberty to irrigate at any time.

R. W. Sorenson: I believe a good many of the companies have adopted the practice in calculating transmission lines for high tension of limiting the capacity in one line to about 20,000 kilowatts. In the paper given by Mr. Wood he stated he would limit the current capacity of a line to 100 amperes. This, of course, means in general that the capacity of any one line is limited to a quantity considerably less than the 20,000 kilowatts frequently used, as only a comparatively small number of lines are operating at a potential of 120,000 volts.

I believe Mr. Wood stated that they used a factor of safety sufficient to allow for the falling of one wire. Is that on a single line, three-phase transmission. Does Mr. Wood allow more strength on a system which has two lines?

A point which is of interest to me in connection with the paper on irrigation prepared by Mr. Ensign, is, can any man pump under his property to keep the water level down and thus keep his own land from souring, or even use the water for irrigation? Can any man drill a well on his property and work on that basis? That may be a familiar question to a lot of people in this section but I am not familiar with anything covering that point.

J. H. Lighthipe: That question has been in the courts of San Bernardino County for ten years. They have dropped salt in one well and used chloride of silver tests half a mile below and injunctions have been placed on well after well. A man there would have a well flowing from 200 to 300 inches of water. They kept digging well after well, soon these would stop flowing and pumping had to be resorted to. Later he would have to go down twelve or fourteen feet. They went so low in one district that in some places the pumps are down in the holes 40 feet. The question of the ownership of subterranean water has been in the courts of San Bernardino county for a great many years, and it is in the courts there today. I don't think it has ever been settled.

Ralph D. Mershon: This paper states that greater trouble is had with low voltages than with high ones. Where such is the case, I do not understand why it should be, unless for the reason stated by the writer of the paper that the engineers have been so used to considering 15,000 volts a low voltage, in connection with which so little care is necessary, that they have not taken the requisite amount of care in the installation of it. In this connection I may say, it seems to me that in some cases high voltages are used where their use is not properly indicated. The design and installation of a high voltage transmission plant is an interesting piece of engineering work, but the adoption of a high voltage for this reason is not, to my mind, engineering. True engineering is based upon economics, and does not indicate the use of a high voltage except where it is economically justified. The object of using a high voltage, rather than a low, is, or should be, to save money. That is, to accomplish by the use of the high voltage something which can not be accomplished otherwise, except at greater expense. But it is certainly not economy, nor, from my point of view, true engineering, to adopt a high voltage, when, for instance, the saving in line copper by its adoption is more than offset by the increase in cost of insulators and transformers. In some cases where a high voltage has been adopted it would appear that economic considerations had not had any part in the decision to adopt it.

These considerations are of special importance in the case of some of the transmission systems in this country, which, instead of being transmission systems pure and simple, are really high voltage distributing systems feeding a very considerable number of comparatively small customers. In such cases it may be much better to adopt a lower line voltage, with a higher cost of line conductor, in order to enable the system to serve small customers, that, at a higher voltage could not be profitably served because of the prohibitive cost of step-down transformers and controlling apparatus.

Referring to the question of lightning arresters. Very good success has been had in the eastern part of this country, and in many places abroad, with the horn type of arresters with graded gaps. That is, from two to four gaps on the same circuit, the gaps being of graded dimensions, the smallest gap having in series with it a high resistance, the larger gaps lower resistances, and the largest gap a fuse.

I can heartily recommend a careful study of the paper read by Professor Creighton at the recent Schenectady meeting of the Institute, which has to do with taking care of arcs to ground; and in connection with that paper the remarks made by Mr. L. C. Nicholson, and a previous paper by Mr. Nicholson relative to a method of protecting pin type insulators against the effects of arcs. The results obtained by Professor Creighton are very interesting, and Mr. Nicholson, who had previously been working along the same lines for over a year, has obtained, on the system of the Niagara, Lockport & Ontario Power Company, results even more remarkable than those reported by Professor Creighton.

There is a question I would like to ask Mr. Ensign. I appreciate that it cannot be answered definitely, but possibly he can answer in a general sort of a way. I should like to know from what depth he has found water can be profitably pumped for irrigation in this part of the country. Another question I would like to ask is as to the total depth of water required in irrigation in this part of the country.

Bearing on the point Professor Sorenson mentioned, the matter of unlimited pumping on your own land has arisen in the Transvaal, especially in the neighborhood of the Vaal River. As I understand it, there are at the present time laws in the Transvaal which prohibit the unlimited pumping of underground waters, because of the fact that by so doing you may rob your neighbor of the water under his land and required by him for irrigation purposes.

I do not entirely agree with Mr. Wood's statement that grounding the neutral of a three-phase system through a resistance results in an indefinite condition as regards the voltage to which the transmission line may be subjected. The voltage will be definite if the proper value be chosen for the neutral resistance. If the resistance be made too high there will be danger of oscillatory effects. But it is possible to adjust the resistance to a low enough value to avoid oscillatory effects, and at the same time sufficiently limit the amount of current which can flow through the neutral. With such an adjustment the maximum voltage that can occur between a line conductor and the ground is something less than that which normally exists between the line conductors.

In the case of the system I have mentioned, that of the Niagara Lockport & Ontario Power Company, the neutral resistance has been chosen low enough to remove the possibility of danger of abnormal voltage, and yet high enough so that when the arc strikes from the cable, or its protecting metal, to the guard ring it will attenuate and go out, of itself, unless, due to wind, or some other condition, it elongates enough to produce a short circuit between line conductors, in which case the automatic mechanism, provided by Mr. Nicholson at the station, operates and extinguishes the arc.

O. H. Ensign: I want to answer a question that someone has raised, Mr. Cory, I believe, about the permanency of the work shown in my paper, in connection with Mr. Lighthipe's experience. It would have been better for Mr. Lighthipe to have had a concrete caisson with pump suspended from the top. Much of the history of the southwest shows a lack of foresight in doing the work in the first instance so as to anticipate conditions one could not forsee because of the short period of experience with the physical conditions of the country. The form of plant described in the paper can not be put out of commission by any probable variation of the water plane.

There are a number of pumping stations where this same thing has occurred, where they have followed the water plane down as the water plane sunk, and got their pumping plant down and could not get it out or use it when the water returned. Having had that in mind, and having had a great deal to do with the development of underground water before I entered the Reclamation Service, we were able to take advantage of that experience in the first plant for which we were responsible. This was the Pima Indian Reservation, which is described in the paper. In this type, you have a well that will last indefinitely. If your water plane does fall, you can still go on further until you reach the point which has been questioned as to the practical depth at which you can lift water for irrigation. That is a question of the nature of the crop and the time and amount of the rainfall that you have in any location.

I have mentioned in the paper that in this valley, Southern California, water is apparently lifted 200 ft. successfully for oranges. I want to qualify that, because the successful growing of oranges is a very indefinite term. A great deal of money is made by a great many people who know how. I honestly believe that you can afford to lift water with economical apparatus something over 100 ft. after you have acquired the grove and it has become a producing property. For the growing of alfalfa I question whether it is profitable to raise water over 30 ft. in small plants even where we can cut six crops per annum, as we do at Yuma and Salt River and some other places. All these things vary, and every community has its own economical points which have to be watched before one goes too far, and it is a very broad and indefinite problem.

The question as to the right to pump underground waters. I believe, that the courts have said in Southern California that you can pump on your own land almost in every case, provided you do not send it off on to somebody else's land and sell it. I believe that is the interpretation of the law. Somebody had better correct me if I am not right on that. But it has been decided that you cannot develop water and transmit it for a general irrigation system in Southern California when that injures prior right. I am not up in law, but that is my memory of one or two cases that have come to my notice.

In the first part of the discussion, the question was asked what to do with the power in the non-irrigation season. That almost solves itself. In the first place, most of the reclamation power plants, Minidoka being an exception, however, are derived from the water which is used for irrigation; that is, the water has been or is being diverted. If it has been stored, it is let out only as needed during the irrigation season, (or it was not worth while to build the dam), and the power so developed of course is used at the same time as it is then wanted for pumping for irrigation, and the two needs exist together and work together as one problem, and in many cases there is no winter pumping to be done at all. It may occur again that there are other power plants on the project for instance, the Salt River Valley Water Users Association have agreed to put up a certain sum of money to build on that project certain power plants, which are made possible by the irrigation works, and with the idea of using them for revenue from the sale of power. The Roosevelt plant was built primarily as a pumping power plant only, although there was existing in the Valley a contract with one of the old irrigation companies with the electric light company in Phoenix, which had to be taken care of, and it has 20 years yet to run. The Reclamation Service is now selling them power from the Roosevelt Dam, but this will be shut off when water is not needed from the dam as soon as these other plants in the valley are built, which are now under contract, and they will use the natural flow of the Verde River and the irrigation water which flows through the canals and are to be located on drops in the canals. Ultimately there may be developed something like 8,000 h.p. besides the power of the Roosevelt Dam.

Something has been said of the capital cost. The capital cost of the Minidoka plant is about $18 per acre so far as the actual power plant, transmission lines and pumping stations, are concerned. The $40 which I mentioned (and which has not been announced as such, but is somewhere in that neighborhood), is the cost of that portion of the project interest in the dam which diverted the water in the first place, and the cost of power and pumping, distributing systems, turn-outs, and all other parts of the system.

Now, there are a number of projects in the United States built by private corporations, and some by the Reclamation Service, in which gravity systems have cost more than that.

Ralph D. Mershon: In figuring these costs, do they include the interest on money during the construction of the dam?

O. H. Ensign: The Reclamation Service is financed by the money received from the sale of government lands, and is loaned without interest to the people who are to pay for it ultimately, the Reclamation Service acting as a trustee, as it were, using this fund, building these works which the people pay for in ten annual payments after the works are finally completed and the cost is known. So the interest is not charged into this cost. They pay no interest on the money whatever. It is mentioned in the paper that there is no interest charge on the money.

The primary idea of the irrigation law was to bring into some degree of value many areas in the west which were beyond the reach of private capital—that is, to irrigate them. I do not believe you could have interested any banker in any sort of irrigation securities in 1902 and 1903. I have heard it stated on reliable authority, and I believe it is true, that up to 1902-3, no private irrigation corporation had ever paid interest on its bonds. That may not be exactly so, but it is nearly so. Very few of them were successful from the standpoint of the investor. The primary cause of that was lack of knowledge of the run-off of the various watersheds in a new country and a lack of interest in the promoter in making sure what that run-off was, and an effort in almost every case to cover more land than the run-off would take care of. They incurred expenses to deliver water, made contracts for water, and sometimes a rather wild finance scheme was attached to the plan, and left the irrigator with a chance to reclaim a portion of the area contemplated if he took hold of the property on the basis of his riparian rights to take care of himself and build it, as in many cases has been done. But the man who put his money into it as an enterprise from which he expected to get revenue, I might say, nine times out of ten received nothing. And the irrigation law came out at that time with the idea of correcting that situation, of bringing together some of these into actual success.

The Salt River Valley presents the most startling fact in that connection. When the Reclamation Service went in to build the Roosevelt Dam, the Valley had been unsatisfactorially served by private corporations. The Salt River is a torrential stream, probably one of the most torrential in the country. I myself have seen it rise from 500 second-feet to 150,000 second-feet in a few hours. It is quite an undertaking for any private capital to build a dam on such a stream. Since the Service started to build that dam, enough water has passed the site to fill it eight times. Just before President Roosevelt opened it, 250,000 acre-feet were stored in it in one day. Floods have passed which would have filled the reservoir in twenty-four hours, and it holds enough water to cover a strip a mile wide and a foot deep from San Francisco to Detroit, Michigan. That is about the best way I can give it to you so you will remember it. It contains 1,300,000 acre-feet.

The Reclamation Act provides that the Secretary of the Interior shall take the funds arising from the sale of public lands and use them for the creation of irrigation works. Practically the only restriction is that no man shall hold over 160 acres of land. If he can make a livelihood, or keep himself busy on less, he shall not have any more land than necessary to support him and his family profitably. In some places it is forty acres; in some places it is eighty acres; Minidoka is eighty; at Yuma there are some places where they think of dividing it up into twenty. The former has ten years to pay for the works in. After the work is complete and the costs are known, the cost is assessed to the land, and liquidated in ten annual payments, plus the actual cost of maintenance and operation during that period, paid by the farmer. In a case like the Salt River, where practically 90 per cent of the land was settled, the government places what amounts to a mortgage on the property to cover the cost before work is begun. There has been a great deal of talk about its being a land speculating scheme where there was no government land the land being already settled. In Salt River Valley they had made effort after effort to control that turbulent stream with continued loss to themselves. Therefore, it was more of a God-send than a speculating scheme that the Reclamation Service could take up the work in the Salt River Valley and make it one of the solidest communities in the whole West.

Coming to this question again of the sale of power, at the Minidoka project, we have an entirely different proposition than we do at Salt River, where we have no real right to generate power except for pumping purposes, except such surplus as may pass the Verde at flood stage or other run-off periods. At Minidoka we have to pass something like 3000 second-feet to the water rights below, during the irrigating season and the remainder of the time the minimum is about 5000 second-feet. In order to keep the operating force the year around and to reduce the all around yearly cost of pumping we are selling power at a very low rate to the several small towns which have sprung up on the project. We are selling this power to those towns at a very low rate in order to bring the towns into a better condition and in order to make them more agreeable places to live, as it is a pretty rugged country in the winter, although a very productive and delightful one in the summer. We hope to build the load up, and are today encouraged that we shall more than pay the operating expenses of the plant during the period it is not operated for pumping. The irrigation season is possibly from the 15th of May until the 15th of October. We have started one season on the 15th of April. In order to get a load that was reasonable from the use of power in the communities, or small towns, we have undertaken to do some heating there. We are selling heating current at a price, I am almost ashamed to mention. But the people themselves, having built these plants with their own money and owning them, and having to stand behind the operation, the prices are not unreasonable. The prices for light and power are just about the same as the adjacent towns. We are selling power for heating at $1.25 a kilowatt a month at a flat rate.

As to the question of developing power and selling it, to reduce the operating cost of the project that has not been authorized. There was a bill passed Congress authorizing the Reclamation Service to sell power, or contract the rental of power sites, up to the limit of ten year contracts. We have under way several construction plants of from 1000 to 1500 kilowatts. They will be used in the construction of dams, and when finished they can be used for whatever purpose desired by the Water Users Association which has paid for these plants in paying for the other works. Undoubtedly there will be found a market for the power and in most cases it will be used largely for pumping.

One or two questions have been asked that I can best answer in a general way by the way we attempted to handle the irrigation pumping problems in this country in the early days of transmission. The first irrigation pumps were started on a 16-hr. basis. Some of them had the privilege at a higher rate of staying over the peak load provided they would cut off on telephone call. That is what is meant by the off-period that has been spoken of, that irrigation may be built up and the valley in the load curve built up and a profitable revenue from that source obtained. There has been one disappointing thing about it. Some seasons were wet seasons, and it would be necessary to shut off irrigation for a long time. In some seasons it diminished to one-half. It is not a load that can be entirely relied upon.

R. J. C. Wood: Mr. Babcock asked at what distance you should switch over from approximate formula to accurate formula in calculating transmission lines. There is no one particular distance where you leave one and get into the other, because they diverge from each other gradually. I would say that up to 150 miles you can use your approximate formula. After you get over that, you had better check it by the correct formula.

He also suggests that more than one conductor may go down at a time. Most of our experience has been that when we get in trouble on the line it is from one conductor to the tower, and it is not between wires; so the switchboard man up in the generating plant, as soon as trouble comes, at once shuts off the current and saves the other wire. The other wire is not involved; there is only one wire involved.

Mr. Downing agrees with me as to the automatic regulator at the generator end, and he states that it is cheaper to install synchronous apparatus than a lot of copper in the line. I believe that is so.

I said there were certain charges necessary more as a statement of fact than as an objection to the system of using synchronous apparatus.

In regard to limiting the capacity of circuits to 20,000 kilowatts or 100 amperes, I think it is the general opinion that it is the number of amperes you break in the switch which does the damage. Possibly basing the switch capacity on amperes is a little better than basing it on kilowats. Mr. Mershon says he was astounded at there being more trouble on low tension than high tension. It may be because there are more miles of the low tension wire that you get more trouble coming in through it, in addition to the fact that it is not built so carefully. I notice he got good results by having resistance series. I suppose you have got to hit the mean between running an ungrounded high tension and a high tension connected solid with the ground. If you are connected solid to the ground you limit your tension on one wire. Can't you put resistance between the neutral and ground? You don't know what you are going to get on that line. The neutral point will shift around and you may get all kinds of voltage, because if the resistance is low, that would indicate the resistance. If the resistance is too low, that will not bother your current. You have to know just what you want.

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THE REFINING OF IRON AND STEEL IN INDUCTION TYPE FURNACES

BY C. F. ELWELL

ELECTRICAL FEATURES

The furnaces for the refining of steel electrically, which have passed the experimental stage, may be divided into two distinct groups, *viz.*, arc furnaces and induction furnaces.

To the former belong the Heroult, Stassano, Keller and Girod furnaces, and to the latter the Kjellin and Röchling-Rodenhauser furnaces. Of the former the Heroult furnace is perhaps the best known and most successful and as comparison always carries more weight than a description, it will be used as the representative of the arc furnaces. The electrical features may be divided up under several heads.

DISTRIBUTION OF HEATING EFFECT OF THE CURRENT

Arc Furnaces. In the Heroult furnace the current passes from one electrode through an arc to the slag, through the slag to the upper metal and thence through another arc to another electrode, and of the current which passes through the carbons only a small percentage passes through part of the metal. As the heating effect of the arc is far greater than any effect of the resistance of the charge, there must be large differences of temperature between different parts of the bath of metal even in spite of the great activity of the bath around the electrodes. This is especially the case with a deep bath of metal. It is for this reason that Girod employs a bottom electrode, thinking thus to have these differences of temperature less by passing all the current for the arcs through the bath. From figures given in Stahl and Eisen for a two-ton Girod furnace, it was computed that the resistance of the carbon electrode was 3800 times that of the bath of metal and so 3800 times more electrical energy was converted into heat in the carbon electrode than in the bath itself. From this it is seen that if the current in the bath of metal produces any considerable part of the heat of the furnace, there must be a large loss of energy in the carbon electrode. The only correction for this is to make the electrodes larger, and the working limit has already been reached. The fact is that the bath is very little heated by the passage of the current and almost all the heating in this type of furnace is done by the very localized heating of the arc. The matter of the losses of energy in the carbons will be taken up under the heading of efficiency.

Induction Furnaces. The principle of the induction furnace is already well known to you but in order to compare the Kjellin and Röchling-Rodenhauser types it will be well to repeat briefly the principle of operation and the type of construction of the Kjellin type. The furnace consists essentially of an iron core around one leg of which is wound a primary winding enclosed in a refractory case and usually cooled by means of forced draught. The annular hearth surrounds this primary coil and is separated from it by means of refractory material. This hearth contains the metal and acts as a secondary winding of one turn. The voltage induced in this turn is quite small so that the energy transformed from the primary coil results in a very large current in the secondary, which heats the metal and thus nearly all the electrical energy is converted into heat in the metal to be melted. The ring being of constant cross section, the heating is about uniform over the whole bath of metal. The Röchling-Rodenhauser furnace has a differently shaped hearth to the Kjellin furnace and a description would not be out of place at this juncture. The furnaces are constructed either for single- or three-phase current. In the former case there are two grooves and in the latter, three grooves. In both cases these grooves, which are similar to the grooves in the Kjellin furnace, open into a distinct open hearth. The cross section of the grooves is comparatively small and they form the secondary circuits in which the currents which heat the metal are induced. Lateral doors are provided so that the contents of the working chamber may be watched, slag drawn off or charge put in. The chief electrical difference between the Röchling-Rodenhauser and Kjellin furnace is that a distinct secondary winding is provided in the former and the current induced is led by means of heavy terminals to plates embedded in the refractory material of the furnace. This refractory material becomes an electrical conductor at the higher temperatures, and this enables an additional circuit to be formed, so that the currents induced in the secondary winding pass through the bath of metal, heating the bath still further. The current also serves to neutralize the great self-induction of the secondary and a better power factor is obtained. The point to be recognized here is that the heating is uniform and not localized as in the Heroult furnace.

VARIATION OF LOAD ON SUPPLY MAINS

Arc Furnace. The instability of an arc is well known and the load on a supply circuit, even with constant watching, varies very greatly. If the furnace has its own generator the regulation can be effected more simply but the best furnace is one which can be connected to regular three-phase supply mains. To do so with the Heroult furnace means motor-driven electrode regulators, etc., and even then the furnace is not a very desirable load.

Induction Furnaces. The changes in load on an induction furnace are always of the intentional kind and sudden changes of load are practically impossible with an induction furnace.

ADAPTABILITY TO CONNECTION TO SUPPLY MAINS

In the question of power factor the Heroult furnace shows some advantage over the Kjellin furnace for in order to build a Kjellin furnace of eight-ton capacity and keep the power factor up to 0.6 or 0.7 it was necessary to lower the frequency to five periods per second. As a five-cycle generator costs more than twice as much as a 25-cycle generator this is a serious question. But with the Röchling-Rodenhauser furnace the current in the second secondary winding can be used to neutralize the effect of self induction to such an extent that a seven-ton furnace may be operated with 25 cycles with a power factor of 0.6 while a three-ton furnace on 25 cycles has a power factor of 0.8. The smaller Röchling-Rodenhauser furnaces are operated from 50 cycles with power factors of 0.85 and 0.8. In my opinion the most economical way to correct this evil is by using fixed condensers which cost only a small percentage of the cost of the furnace and the power factor may be made as high as desired.

ELECTRICAL EFFICIENCY

Arc Furnaces. The before mentioned Girod furnace with but one electrode of 14 in. (35.5 cm.) diameter and a current of 6200 amperes at 60 volts showed a power loss of 10 per cent in the electrode alone. In the Heroult furnace the current is in general smaller but there are two electrodes in series and the result is about the same. Not only is energy lost in the electrodes by reason of their high resistance but a large amount is also lost by means of the water cooling of the jackets which is necessary because of their high conductivity for heat. The cost of maintenance of carbon electrodes is also considerable. Radiation loss is greater with the arc furnaces because a great deal of the heat of the arc is reflected to the roof which must be water cooled to last, and even then has to be renewed about every 14 days.

Induction Furnaces. Tests made on a 3.5 ton furnace at Volklingen have shown an electrical efficiency of 97 per cent which is a contrast to the 10 per cent lost in electrodes alone in arc furnaces. The electrode plates never wear out for they do not come in contact with the molten metal or slag and the portion of the lining which acts as a conductor has been found in practice to last longer than any other portion of the lining.

SUMMARY OF ELECTRICAL FEATURES

a. Heating of metal bath is much more uniform in induction furnace.

b. The variation of load is much less with the induction furnace.

c. The adaptability to connection to existing power networks is in favor of the induction furnace.

d. The efficiency is in favor of the induction furnace.

METALLURGICAL FEATURES

The earlier induction furnaces, *i.e.*, those of the Kjellin type did not show many metallurgical advantages except that it was possible to treat much larger charges than with crucible methods. They were quite unsuited to working with slag because of the shape of the hearth and so only served to melt pure materials. The shape of the Röchling-Rodenhauser furnace is such that slags can readily be handled and refining carried on. At the same time it can be used for smelting work whenever necessary, and as much larger charges can be worked, a considerable saving is made in crucible steel working.

The advantages of the electric furnace are:

1. On account of the convenient regulation of the temperature attainable the phosphorus can be removed until only a trace remains.

2. It is especially suitable for the most thorough desulphurization.

3. When the refining is complete, the charge can be left in the furnace as long as may be desired without change of composition.

At Trollhattan, Sweden, the furnace is started by means of a ring of metal. The cold materials are charged gradually until all are melted. Continuous operation is possible by leaving a portion of the molten metal in the furnace after each teeming.

At Volklingen, Germany, the furnaces are supplied with molten metal from basic Bessemer converters which contains about 0.08 per cent S and 0.08 per cent P. The extent of the dephosphorization and desulphurization depends on what the steel is wanted for.

An oxidizing slag is formed from lime and millscale or ore, which is removed as far as possible when dephosphorization is complete. The re-carburization takes place and a slag free from iron is formed for desulphurization. A typical slag for desulphurization has a well-known white appearance and falls to a white powder on exposure to the air. When the slag has this property, the charge may be left as long as desired in the furnace. The furnaces are entirely emptied after each charge as the molten converter steel allows the load to be readily brought to a satisfactory figure.

When not working, about one third of the normal energy will keep the furnace hot. The seven-ton furnace at Volklingen has been 30 hours without taking any current and was heated up again with normal energy consumption. Within half an hour the metal began to glow and regained its normal temperature after four hours and the charge was finished up in the regular way. At the works at Volklingen no work is done on Sunday but there is no difficulty in starting up the furnaces with unfinished charges from the previous Saturday.

The natural circulation which takes place in induction furnaces serves to thoroughly mix the charge and the management of the Poldihütte, Austria, made a test in which seven samples were taken from six different places in the furnace and the analysis of these samples is shown in the following table:

	Carbon Per cent	Manganese Per cent	Silicon Per cent	Phosphorus Per cent	Sulphur Per cent	Chromium Per cent
1	0.81	0 27	0.335	0.031	0.007	1.00 1.01
2	0.77	0 25	0.340	0.030	0.008	1.00 1.01
3	0.85	0 28	0.345	0.029	0.007	1.00 1.01
4	0.82	0 27	0.335	0.030	0.009	0.98 0.99
5	0.78	0.25	0.335	0.030	0.009	0.99 0.96
6	0.78	0.27	0.419	0.031	0.010	0.99
7	0.79	0 28	0.326	0.030	0.009	0.98

The furnace was teemed 37 minutes later and a sample cast out of the ladle gave the following analysis:

Carbon	0.77 per cent
Manganese	0.29 "
Silicon	0.396 "
Phosphorus	0.031 "
Sulphur	0.009 "
Chromium	0.99 "

That the Röchling-Rodenhauser furnace is no longer an experiment is shown by the fact that the 3.5-ton furnace was worked for a whole year producing steel for rails, and more than 5,000 tons have been sold. The eight-ton furnace has been running since November, 1908, an average of 14 days to a lining and 1,200 tons of rails to a lining. The management contemplates the building of a 16-ton furnace as the next step.

At Dommeldingen the two-ton furnace is used to refine crude pig iron.

	Analysis of charge	Analysis of cast
Carbon	4.0 per cent	0.5 per cent
Phosphorus	1.8 "	0.025 "
Sulphur	0.2 "	0.03 "
Manganese	0.0 "	0.76 "
Silicon	1.05 "	0.056 "

Breaking strain	95,000 lb. per sq. in.
Elongation	20 per cent
Contraction of area	36.33 "
Duration of conversion	5 hours.

SUMMARY OF METALLURGICAL FEATURES

1. Having no electrodes, facilities are provided for heating the bath without introducing impurities and the charge may be left indefinitely in the Röchling-Rodenhauser furnace without change.

2. Having a large open hearth, (in the 1.5-ton furnace it is 60 by 26 in. or 1.52 by 0.65 m.) with doors it is possible to do any class of refining in the Röchling-Rodenhauser furnace much the same as in the open hearth furnace.

3. When the hearth doors are closed the Röchling-Rodenhauser furnace is air-tight and may be left for long periods without great loss of heat, making intermittent working possible.

4. The natural gentle movement of the charge allows of complete mixing of the ingredients of the charge, and is not sufficient to attack the lining.

COSTS

Royalty. The German users of the induction furnace pay $0.65 per ton for rail steel and $1.50 per ton for crucible quality steel. This is for small daily production. For 1000 tons daily the royalty is placed at $0.36 per ton for rail steel and for 1200 tons daily it is $0.50 for crucible quality steel.

Energy Required. A great many figures have been given out most of which were for small furnaces and special runs. The plants at Trollhattan and Volklingen being in commercial operation supply the most reliable figures obtainable.

Cold Pig and Scrap. With cold materials, refining, etc., to crucible quality steel is done with 600 to 900 kw-hr. per ton according to the size of the furnace.

Hot Pig and Scrap. With hot pig iron and cold scrap crucible quality steel is obtained with 300 to 700 kw-hr. per ton according to the proportions of the two ingredients and the size of the furnace.

Hot Metal from the Converter. Converter material with an analysis of P, 0.08 per cent; S, 0.08 per cent; Mn, 0.5 per cent; C, 0.1 per cent is refined to steel for rails with an analysis of P, 0.05 per cent; S, 0.04 per cent; Mn, 0.85 per cent; C, 0.5 per cent with 100 kw-hr. per ton in a seven ton furnace. Same material is refined to high quality steel showing only traces of P and S; Mn, 0.2 per cent; C, 0.5 per cent with 250 kw-hr. per ton.

Hot Metal from Open Hearth Furnace. Material from open hearth furnace, already dephosphorized and desulphurized and containing 1.22 per cent C; Mn, 0.38 per cent; Si, 0.21 per cent to high quality steel with 200 to 250 kw-hr. per ton.

Cost of Production. (1) *For a 1.5-ton furnace melting scrap and refining to pour best steel for steel castings. Furnace of the three-phase, tilting type. 50 cycles, 210 kw. and power factor 0.80.*

Interest Charges. Cost with all accessories about $9,000. With 10 per cent for interest charges gives $900 annually. Using 290 working days in a year and six charges, 3 to 3.5 hours each, daily and 1500 lb. to a charge gives 4.2 tons daily and 1,220 tons yearly. This is equivalent to about 21 hours working. Cost per ton for interest, $0.74.

Labor. Two men can attend to this furnace with ease, as the electrical part requires no special attention. The melter adjusts the temperature and watches the metallurgical process. The helper sees to the fan and charging etc. Allowing two shifts and $5.50 per shift or $11 daily gives a labor cost of $2.62 per ton of steel.

Lining. Relining may be done every 8 or 14 days. It takes three tons of magnesite and 0.36 ton of tar to completely reline the furnace. The relining is done with half new material and half old. For getting out the old lining, mixing material and putting in the new, four men are allowed 16 hours. Cost of lining per ton of steel, on an average, $1.50.

If lined with dolomite, which is cheaper, and every 14 days then lining cost allowing one third material recovered is $1.00 per ton of steel.

Keeping Warm. When the furnace is not used for several hours during the night, it must be kept warm, for which about a third of the working amount of energy is necessary. In this way if normal energy is 200 kw. then about 200 kw-hr. will be necessary to keep the furnace warm over the three-hour period of rest. For six working days this is necessary five times and 1000 kw-hr. must be charged up to heating.

Cost of keeping furnace warm at $20.00 per kw-yr. is $0.09 per ton of steel.

Cooling of Transformer. The blower takes a 2.5-h.p. motor or 1.8 kw. and for 24 hours = 43 kw-hr.

Cost of cooling transformer per ton of steel, $0.02.

Energy Consumption. From cold materials about 850 to 900 kw-hr. are necessary, in this size furnace. Taking larger figure the cost of energy per ton is $2.06.

Royalty. In the United States, on the basis of a plant of 50 tons daily the royalty would be about 50 cents per ton.

SUMMARY OF COST

Interest charges	$0.74
Labor	2.62
Lining	1.50
Keeping furnace warm and cooling	0.11
Royalty (approx.)	0.50
Energy for melting and refining	2.06
Total	$7.53

The figure $7.53 is the working cost which must be added to the cost of the materials in order to find the cost of crucible quality steel from scrap. The above figure would be more reasonable with larger furnaces.

Cost of Production. (2) *For a two-ton, 300 kw., three phase tilting furnace.—Molten converter steel to quality steel for castings.*

Cost with all accessories about $12,500. With 10 per cent for interest charges gives $1250 per annum. Allowing 250 working days in the year and 16 tons per day gives 4,000 tons per annum or $0.31 per ton of steel.

Interest charges per ton of steel	$0.31
Power for heating up, per ton of steel	0.02
Power for refining, allowing upper figure of 300 kw-hr. at $20 per kw-yr.	0.68
Air cooling of furnace core	0.01
Cost of lining every ten days. (German figure.)	0.35
Wages allowing $16 per day	1.00
Royalty on basis of 50 tons daily	0.50
Total cost per ton of steel	$2.87

This figure would give a good idea of the cost of converting molten pig iron into steel, exclusive of the ferro alloys.

Cost of Production. (3) *For a five ton, 550 kw., three phase tilting furnace.—Molten converter steel to crucible quality steel.*

Cost with all accessories about $22,000. With 10 per cent for interest charges gives $2,200 per annum. Reckoning 250 working days in the year, each one with eight heats of five tons, the yearly production would be 10,000 tons, or $0.22 per ton for interest charges.

Interest charges	$0.22
Power including heating up. For a monthly average of 230 to 280 kw-hr. per ton and taking the higher figure	0.64
Cost of lining. (German figure.)	0.30
Wages allowing $20 per day	0.50
Air cooling of core	0.01
Royalty (Approx.) Basis of 50 tons daily	0.50
Total	$2.17

Cost of Production. (4) *For a seven ton, 750 kw., three-phase, 25-cycle, 0.6-power factor tilting type furnace.—Converting molten converter steel into high grade rails. For analysis see page 626.*

Cost with all accessories $27,000. Interest charges at 10 per cent gives $2700 per annum. Allowing 100 tons daily (the makers claim a production of 140 tons) and 250 working days in the year gives a yearly production of 25,000 tons of rail steel and interest charges per ton of steel = $0.11.

Interest charges	$0.11
Power for heating up	0.01
Power for refining. Makers claim 100 kw-hr. per ton. Allowing 150 kw-hr. per ton	0.34
Power for cooling	0.01
Cost of lining. Pneumatically tamped. Two foremen and six laborers or $21.00 daily. Per ton	0.02
Cost of lining material. (German figure)	0.06
Wages. Two head melters at $3.00 and 10 helpers at $2.50 $31.00 per ton	0.31
Royalty on rail steel, one furnace in U. S	0.35
Total	$1.21

This is the conversion cost which added to the value of the pig and ferro alloys, etc., gives the cost of steel for rails. The Prussian Railways paid $10 extra per ton for rails made in this furnace and were well pleased with the product.

Cost of Production. (5) *For a seven-ton, 750-kw., three-phase, 25-cycle, 0.6-power factor, tilting type furnace.—Molten converter steel to highest quality steel. For analysis see page 626.*

This furnace will produce about half the steel of this quality as when working on rail steel or 50 tons daily.

The cost per ton under these conditions is about $2.00 per ton including royalty.

SUMMARY OF COSTS OF PRODUCTION EXCLUSIVE OF MATERIALS

1.5-ton furnace melting scrap and refining to pour high grade steel for castings. Per ton	$7.53
2-ton furnace refining molten converter steel to high grade steel. Per ton	2.87
5-ton furnace refining molten converter steel to high grade steel. Per ton	2.17
7-ton furnace refining molten converter steel to high grade steel. Per ton	2.00
7-ton furnace refining molten converter steel to high grade rails. Per ton	1·21

DISCUSSION ON "THE REFINING OF IRON AND STEEL BY INDUCTION TYPE FURNACES," LOS ANGELES, CAL., APRIL 25, 1911.

R. J. C. Wood: I notice here it says one-third of the energy is used in radiation losses. If the radiation loss amounts to one-third of the working amount, I don't see how they could get 97 per cent efficiency.

R. W. Van Norden: I cannot answer the question exactly but I imagine that what Mr. Elwell means is the furnace or transformer efficiency. Taking into consideration the heating of the hearth, it would not have that efficiency. There are no published figures on the furnaces on the Pitt; there are no induction furnaces there and I don't believe they intend to install any as they are very well satisfied with the electrode type. They are not the Heroult furnace, but a modification of an earlier type which the operators have worked out themselves. I can not give any figures on operation and costs. I understand that refined pig-iron can be laid down in San Francisco at $18 a ton, or less.

Earl W. Paul: I am slightly familiar with the process of reducing iron ores and the making of steel by the Bessemer and open hearth processes, and know how important it is that the product of the furnaces should show a uniform chemical analysis.

From the data given in the paper it appears that the product of the electric furnace runs remarkably uniform, and further that at small cost the iron or steel can be kept in a molten condition and treated until the desired chemical analysis is obtained.

Another very important feature, is that, the chilling of the furnace is not a serious matter. Should the furnace chill, the current can be turned on the solid mass and in a few hours is remelted. The chilling of the present type of furnace, usually means quite a serious loss.

J. J. Frank: I had occasion during the last week to visit one of the large steel manufacturing companies, and I saw an arc furnace and discussed it with one of the attendants, and he remarked that the handling of the electrode is one of the most difficult things. It was a Heroult furnace. When the carbon drops off into the bath, it of course affects the chemical analysis. The attendant also told me that while the steel produced met the chemical analysis, it did not always live up to the same physical requirements; that is, the results vary.

I am a little familiar with the induction type furnace, and I would like to add to the remarks of the author by saying that there is a type of induction furnace in which the primary winding is a hollow tube. This primary is supplied with current from a transformer stepping it down from 10,000 volts or any other voltage which may be available. Water flowing in this copper tube keeps it cool, so a very high current density is possible, and it will influence the operation of the transformer because of its increased weight. One of the objections to the arc furnace, whether it is the Heroult or any other furnace, is the heat from the furnace affects the reliability of the induction motor operating the electrodes. At first glance, that is not very important, but when you consider that any fumes which pass off naturally ascend and if the induction motors are directly over the furnace the fumes will influence the insulation and the action of the induction motors, it is more important; and that, I believe, is one of the serious problems in the construction of these arc furnaces; namely, to take care of and protect the induction motors from these fumes.

Another problem is the installation of the induction motors and the gearing that is necessary. The induction motor must be clamped directly to the electrodes, and that must be the potential of the furnace. Another objection is, in an arc furnace, the arc may create high frequencies, which being transformed to the high potential side of the transformer, affect the operation and may disturb the whole system so that it may induce stresses in the transformer which cannot be foreseen until the operation is begun.

H. H. Sinclair: Are the furnaces mentioned treating pig iron into steel? I had the impression, and I would like to ask Mr. Van Norden if it is not true that in the works of the Noble Steel Company, they were treating iron ore and converting it into pig iron.

R. W. Van Norden: There is no attempt to refine the iron. Pig iron only is made from iron ore.

H. H. Sinclair: What type of iron ores do they get, magnetic ore or one of the others?

R. W. Van Norden: It has a high percentage of iron, about seventy per cent.

H. H. Sinclair: I think that they treat a magnetite ore in Shasta County.

J. J. Frank: With the induction type of furnace it is possible, as I stated, to use a transformer scaling down from any high voltage to the primary of the furnace and that primary charge might be a very minor one and is copper through which water circulates and the insulation is just rubber hose. The problem there is a very simple one.

Another point raised here is the variation of the voltage. That may be very readily done in the induction type by an ordinary regulator. It would make it very easy to regulate and momentarily give 200 per cent overload current if it was desired to very rapidly heat the charge.

R. W. Sorensen: In connection with this kind of work I believe there is one feature the effect of such a load upon the supply source which must be carefully considered. The author states that a better load is put upon the line when the induction furnace rather than a furnace of the electrode type is used, but has not called attention to the fact that with the use of the electrode type of furnace it is impossible to balance the polyphase power line except by means of a motor-generator set which changes the polyphase current to either single phase alternating, or direct current; because of that old rule " a single phase current pulsating power cannot be turned into an equivalent polyphase current, or *vice versa*, without some rotating devise which will balance the transfer of energy."

Another point in favor of the induction type of furnace is that there is less liable to be such rapid fluctuation of current as will probably occur with the electrode type when there is any change in position of electrodes or in the conducting property of the charge. Suppose your electrode moves slightly. If you have, as the author states, 6200 amperes, for instance, and the voltage produced by the varying of that current is anything like what we have with transmission lines or was mentioned a few moments ago, *viz.*, 200 times the current interrupted, you would have a tremendous amount of power that would have to be taken care of somewhere. Now suppose your current varies but ten per cent, that would still leave you something over a hundred thousand volts to be taken care of in what is probably a low voltage system. Of course, it is very probable that the voltage variation in the supply transformer will not be anything like the voltage thus induced on a line but on the other hand it may be more. Just what law this would follow I don't know, but I am quite sure that a transformer for this kind of service should be made especially for this service because if these larger variations take effect on transmission lines, a certain percentage of that voltage variation must take place where you have magnetic circuit in the transformer, so if you are going to use transformers, for such service, special care should be exercised or you will have trouble with your transformers supplying to electrodes such large current as 6200 amperes.

C. W. Koiner: In addition to what Professor Sorensen has just stated, I would add that these furnaces operate to give the companies additional field in which to sell current. In 1904, we are told there were only four electric furnaces in existence, and they were in Europe. Today we have over one hundred, ranging in size from 100 lb. to 15 tons. These are used in this country and in Europe. There has been a furnace in operation in South Chicago for the past year or so and I understand it gives very good results. We are also told that current is now being sold at off-take periods for the refining of steel at a cost of about one cent per kw-hr. This has been going on for about a year. The cost is very reasonable when you consider it in comparison with the cost in refining operations.

Budd Frankenfield: It seems to me we along the Coast here should be especially interested in electric furnaces, not for the smelting of steel particularly, but electric furnaces in general. I would not regard it as an off-take proposition, because in furnace industries such as we have at Niagara, they operate twenty-four hours in the day. They have a large enough load factor to keep up a continuous demand for current.

Another thing is the large amount of power that can be used by these furnaces. For instance, it would not take a very large plant in some electrochemical or electric furnace industry to use the entire Owens River power which we expect here, to found an industry and employ men, instead of spending a great deal of money for a general distribution system. I have no doubt there are plenty of raw materials on the Pacific Coast to be utilized in making furnace industries, such as are in existence in Europe, a good proposition and a success.

C. H. Vom Baur: The Kjellin induction furnaces being put out today are chiefly of the small, laboratory sizes, as the Rochling-Rodenhauser electric induction furnaces have three distinct advantages over the Kjellin, which give it undoubted preference as follows:

1. It operates on polyphase current and in the one and two-ton sizes at 50 or 60 cycles with a power factor of 0.7 to 0.8.

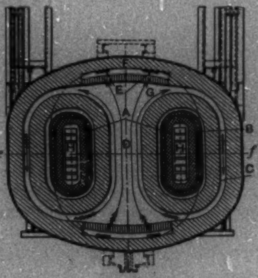

FIG. 1

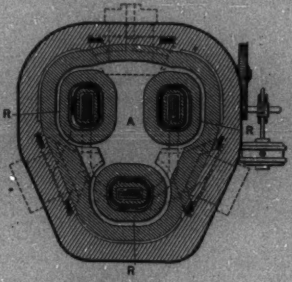

FIG. 2

2. Owing to the different shaped hearth, that is, having two or three intersecting circuits making a large hearth in the center, as shown in Figs. 1 and 2 herewith, and on account of the auxiliary, secondary current which is usually 30 per cent of the whole, which also goes through the bath, the so-called "pinch effect" or interruption of the circuit is absolutely precluded. This was one of the greatest disadvantages of the Kjellin furnace.

3. The larger hearth thus made allows a *rapid* refining of steel.

One of the greatest advantages of the induction furnace not mentioned by Mr. Elwell is its aptitude for thorough deoxidation of the metal and absence of segregation.

Relative to the magnesite lining, improvements have lately been made so that this now lasts three weeks instead of two weeks as formerly.

One of the metallurgical features, not mentioned, which is of some moment as it saves time, is that the power and thence the maximum heat remains on the furnace when rabbling off the slag. In an arc furnace the carbons have to be withdrawn for this operation.

As Mr. Elwell assumes that current is made for $20 a kw-yr., it is hardly possible that current would be used all the time and the practical probability is that the current would be in use not over ⅔ or ¾ of the time, costing therefore 33 or 50 per cent more per kw-hr. It would perhaps have been better if Mr. Elwell had also added the cost of the usual ferro alloys and fluxes, such as lime, roll-scale, etc., to the conversion cost for the sake of completeness. These fluxes and additions usually cost from 60 cents to $1 per ton.

The summary of costs of production inclusive of fluxes, taken at $1, and allowing for actual cost of electricity, at 50 per cent increase, would more nearly be as follows:

1.5-ton furnace melting scrap and refining to pour high grade steel for castings. Per ton	$9.61
2-ton furnace refining molten converter steel to high grade steel. Per ton	4.22
5-ton furnace refining molten converter steel to high grade steel. Per ton	3.49
7-ton furnace refining molten converter steel to high grade steel. Per ton	3.18
7-ton furnace refining molten converter steel to high grade rails. Per ton	2.39

C. F. Elwell: The efficiency of 97 per cent refers to the electrical efficiency of the transformer. The core is built up of slightly heavier iron than usual and these laminations are separated by sheets of India paper. The core and copper loss in the primary is under these circumstances about 3 per cent. Similar electrical losses, not radiation losses, in the arc furnace are very much greater. The high resistance carbon electrodes dissipate a large amount of energy. It is true that the radiation loss is high as evidenced by the amount of power necessary to keep the furnace from freezing over a period of rest. The arc furnace is notorious for its radiation for in my experience it was very difficult to keep a top on one, and without a top the heat in the furnace room was unbearable. One point in favor of the Rochling Rodenhauser furnace is that most of the bath can be well covered to prevent radiation as it is unnecessary to remove the covers except for relining.

In reply to Mr. Sinclair, the iron ore in Shasta county has an analysis as follows: Fe 69.9 per cent; Fe_3O_4 89.4 per cent; Fe_2O_3 0.3 per cent; Mn O 0.18 per cent; Mg O 0.3 per cent; $Si O_2$ 2.4 per cent; P 0.011 per cent; S 0.009 per cent.

Considerable pig iron has been made but as yet the furnace does not last long enough to bring the cost per ton for furnace relining to a reasonable figure.

Professor Sorensen sounds a note of warning which it might be well to heed even if some of us have had no trouble from this source. I have had experience with 22,000 amperes and the whole load has been dropped suddenly many times but no ill effects have been noticed in the transformers.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 25, 1911.

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CISOIDAL OSCILLATIONS

BY GEORGE A. CAMPBELL

The oscillations here defined as "cisoidal oscillations" are those of the form

$$C \operatorname{cis} pt = C(\cos pt + i \sin pt) = Ce^{ipt} \qquad (1)$$

where t is the time, e the Napierian base, $i = \sqrt{-1}$ the imaginary symbol,[1] and cis an abbreviation for the complete trigonometric expression. The constants C and p may be any scalar quantities, either real or complex. The oscillations are sustained, logarithmically damped or aperiodic, according as the time coefficient p is real, complex, or pure imaginary. The following discussion will, in general, apply indifferently to all three cases.

The use of the term "cisoidal oscillations" emphasizes the distinctive character of the subject, while tending to keep in mind the close connection between these oscillations and sinusoidal oscillations. The fact that one of the algebraic curves is called a "cissoid" can hardly lead to confusion.

The practical importance of cisoidal oscillations rests upon the following properties:

1. In all cases where the principle of superposition holds, any

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[1] The use of i (or Greek ι) for the imaginary symbol is nearly universal in mathematical work, which is a very strong reason for retaining it in the applications of mathematics in electrical engineering. Aside, however, from the matter of established conventions and facility of reference to mathematical literature, the substitution of the symbol j is objectionable because of the vector terminology with which it has become associated in engineering literature, and also because of the confusion resulting from the divided practice of engineering writers, some using j for $+i$ and others using j for $-i$.

oscillation may be regarded as a compound cisoidal oscillation, *i.e.*, the algebraic summation of simple cisoidal oscillations.

2. Cisoidal oscillations are uniquely simple because the ratio of the instantaneous electromotive force to the instantaneous current is not a function of the time.

3. Cisoidal oscillations involve scalar magnitudes only so that all algebraical relations and operations applying to the real physical phenomena may be extended to them.

4. The solution for cisoidal oscillations in any finite network may be written down directly, without solving differential equations or the use of integration or differentiation.

SCALAR CHARACTER OF CISOIDAL OSCILLATIONS

As complex quantities and exponential functions of complex quantities follow the laws of ordinary algebra, they introduce scalar quantities and not vector quantities. This is a matter of great importance, since ordinary algebra is simpler than vector algebra. The wide-spread use of the term "vector" in connection with complex quantities in alternating current theory is unfortunate for it is logically incorrect, and so has led to confusion, and it also tends to divert attention from the algebraical theory of complex quantities, which is of great practical assistance in the treatment of cisoidal oscillations.

When the direction of a current is confined to one or the other of two opposite directions by the use of a linear conductor, we can vary its scalar magnitude only; it is no more correct to speak of representing this scalar quantity by a vector when it is complex than when it is real. It is only when the electrical phenomena takes place in two or three dimensions in space that vector variables are involved in the mathematical treatment.

With complex quantities the power continues to be the product of electromotive force and current. A steady imaginary current flowing through a resistance, therefore, dissipates negative real power, that is, energy is absorbed by the electrical phenomena taking place, which tends to cool the conductor. Similarly the magnitudes of the kinetic energy of an inductance and the potential energy of a condenser are real negative quantities in case the instantaneous current and potential are pure imaginary. As the power with complex quantities may be either positive or negative, or in general have any argument, the total power in a portion of a network, such as two or more resistances, may vanish because the several powers in the individual elements mutually cancel when added together.

If the current and electromotive force are each cisoidal the associated power is also cisoidal with a time coefficient equal to the algebraical sum of the time coefficients of the electromotive force and current; when these two coefficients are equal and opposite in sign the power is constant with respect to the time.

We might have defined the cisoidal oscillation using throughout $-i$ in place of i, which would change all quantities, including the impedances, to their conjugates. But we follow, of course, the general practice of taking positive quantities as the norm, in consequence of which the sign for inductive reactances is positive, and the sign for capacity reactances is negative.

CORRELATED OSCILLATIONS

The complete formal solution of a sinusoidal alternating current problem by the aid of complex quantities involves the following steps:

1. Resolution of the periodic data into the sum of cisoidal oscillations having the time factors cis $(+pt)$ and cis $(-pt)$.
2. Solution of the problem for the cis $(+pt)$ component taken alone; the solution for the cis $(-pt)$ component is then obtained directly from this by changing all complex quantities to their conjugates.
3. Superposition of these two cisoidal solutions to obtain the real physical oscillation.

It is however not necessary to carry through the formal proof in individual cases, this being replaced by the following correlation between the real and the complex oscillations.

If throughout any invariable network a cisoidal oscillation and a cosinusoidal oscillation (all of one time coefficient p) have electromotive forces and currents of the same effective values (moduli) and angles (arguments), they will be called correlated oscillations.

The alternating powers involved throughout correlated oscillations are equal to each other as regards amplitudes (moduli) and angles (arguments); the cosinusoidal oscillation having also non-alternating power components which are equal, as regards amplitudes (moduli) and phase angles (arguments), to the powers which would be associated with the correlated cisoidal electromotive forces taken with the conjugates of the correlated cisoidal currents.

Or in other words:

The instantaneous cosinusoidal electromotive forces and currents are the real components of the correlated cisoidal electromotive forces and currents multiplied by the factor $\sqrt{2}$.

The instantaneous powers involved in a cosinusoidal oscillation are equal to the real components of the cisoidal powers in the correlated cisoidal oscillation, augmented by the real components of the powers involved in the correlated cisoidal oscillation after changing the currents (or electromotive forces) to their conjugates.

In the typical notation the correlated oscillations thus defined have, if $p=p_1+p_2 i$

Instantaneous	Cisoidal	Cosinusoidal	
e.m.f.	$E e^{ipt}$	$\sqrt{2}\lvert E\rvert e^{-p_2 t}\cos(p_1 t+\arg E)$	
current	$I e^{ipt}$	$\sqrt{2}\lvert I\rvert e^{-p_2 t}\cos(p_1 t+\arg I)$	(2)
power	$E I e^{2ipt}$	$\lvert E I\rvert e^{-2p_2 t}\left[\cos(2p_1 t+\arg(E I))+\cos\arg\frac{E}{I}\right]$	
impedance	$\frac{E}{I}$	$\left\lvert\frac{E}{I}\right\rvert\frac{\cos(p_1 t+\arg E)}{\cos(p_1 t+\arg I)}$	

In much of the actual algebraical work connected with cisoidal oscillations, we may drop the time factors e^{ipt} and e^{2ipt} and write only E, I and $E I$ (or $P=E I$) with considerable resulting simplification and no liability of introducing confusion.

It is to be particularly noted that the magnitudes which are equal to the corresponding cisoidal moduli are the *effective* values of the cosinusoidal electromotive forces or currents and the *amplitudes* of the cosinusoidal power components. On the other hand, the cisoidal arguments are uniformly equal to the corresponding real angles, this angle reducing for the non-oscillatory cosinusoidal power component to the constant angle of lag or lead.

The preceding statements supply the working rules for making the change from the real physical cosinusoidal oscillation to the ideal cisoidal oscillation and vice versa. This connection is, as regards electromotive force and current, one of mutual resolvability as is expressed by the following formulæ:

$$\sqrt{2}|C|e^{-p_2 t}\cos(p_1 t+\arg C)=\frac{1}{\sqrt{2}}Ce^{ipt}+\frac{1}{\sqrt{2}}C'e^{-ip't}$$

$$C e^{ipt}=\frac{1}{\sqrt{2}}\left[\sqrt{2}|C|e^{-p_2 t}\cos(p_1 t+\arg C)\right] \qquad (3)$$

$$+\frac{i}{\sqrt{2}}\left[\sqrt{2}|C|e^{-p_2 t}\cos\left(p_1 t+\arg C-\frac{\pi}{2}\right)\right]$$

the first giving the cosinusoid in terms of the correlated cisoid and its conjugate cisoid, the second giving the cisoid in terms of the correlated cosinusoid and the consinusoid with its phase retarded 90 degrees. On account of this mutual resolvability either the cisoidal oscillation or the cosinusoidal oscillation may be regarded as being obtained by summation from the other.

If any particular cisoidal or cosinusoidal oscillation is possible the correlated oscillation is also possible.

It is somewhat arbitrary as to the exact functions which we define as correlated oscillations. The sine might have been taken in place of the cosine and the amplitudes in place of the effective values, but on the whole these alternatives do not seem to afford quite the same convenience, but only because the statements become slightly more involved. We shall however continue to use the term " sinusoid " as the general designation for the sine function having any arbitrary phase angle including thereby the cosine function.

The correlation between the sinusoidal oscillations and cisoidal oscillations is so simple that it is not ordinarily necessary to indicate the step from one to the other in special applications of the method. But this omission has led to the cisoidal solution being in some way regarded as representing the actual sinusoidal oscillation, which is not the case as is very clearly shown by the power relations. It is therefore necessary to lay emphasis upon the fact that the use of complex quantities affords an indirect method, and not a symbolic method of solving real cases of oscillations and that the complete application of the method involves an initial algebraical resolution of the real data and a final algebraical summation of the complex results as an essential and integral part of the method.

GENERAL EQUATIONS FOR ANY NETWORK

In any invariable network the actual distribution of current due to any impressed electromotive forces is such as to make the power dissipated assume the stationary value[2] *which is consistent with the conditions imposed by current continuity and the conservation of*

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[2] A function assumes a stationary value when it is not altered by any possible infinitesimal change in the system of variables upon which it depends; the first derivatives of the function, with respect to each of a set of independent variables is zero at a stationary value. Stationary is thus a generalization of maximum, minimum and point of inflection, but without any implication beyond the vanishing gradient.

energy. The theorem assumes that each branch or circuit contains resistance, a condition which corresponds to the physical fact and involves no theoretical limitation as the resistances may be as small as desired, or any number of the resistances may be allowed to vanish completely after playing their part in the formation of the general solution.

This theorem may be established directly from the principles of dynamics, but we will here show that it is the equivalent of the generalized Kirchhoff equations.

The condition imposed by the conservation of energy may be expressed in the form of the equation of activity by equating the total power supplied by the impressed forces to the sum of the powers taken separately by the resistances (including conductances), self-inductances, mutual inductances and capacities. That is

$$\sum e_q i_q = \sum R_q i_q^2 + \frac{d}{dt}\left(\sum \frac{1}{2} L_q i_q^2 + \sum M_{qr} i_q i_r\right)$$

$$+\frac{d}{dt}\sum \frac{(\int i_q\, dt)^2}{2\, C_q} = \sum R_q i_q^2 + \sum L_q i_q \frac{d\, i_q}{d\, t}$$

$$+\sum M_{qr}\left(i_q \frac{di_r}{dt} + i_r \frac{di_q}{dt}\right) + \sum \frac{i_q \int i_q\, dt}{C_q} \qquad (4)$$

The condition of continuity may be introduced by expressing the currents in terms of any set of independent, circuital currents $c_1, c_2, \ldots c_n$, where n is the number of degrees of freedom of the network. This gives one equation for each of the l branches

$$i_q = a_{q1} c_1 + a_{q2} c_2 + \ldots a_{qn} c_n \qquad (q=1, 2 \ldots l) \qquad (5)$$

where the coefficient $a_{qs} = \pm 1$ or 0, according as branch q is or is not a part of circuit s, the sign in the first case being positive, or negative, according as the positive direction for the branch and for the circuit are or are not concurrent.

The power dissipated $\Sigma R_q i_q^2$ is a homogeneous expression of the second order in terms of the n independent circuital currents, while the remainder of equation (**4**) is of the first degree in these currents. The stationary value for the power dissipated under the assumed conditions will therefore be found by first introducing the multiplier $\frac{1}{2}$ as a coefficient for $\Sigma R_q i_q^2$ and then differentiating (4) with respect to c_s[*] which gives the following set of n equations:

$$\sum a_{qs} e_q = \sum a_{qs} R_q i_q + \sum a_{qs} L_q \frac{di_q}{dt} + \sum M_{qr}\left(a_{qs} \frac{di_r}{dt} \right.$$

$$\left. + a_{rs} \frac{di_q}{dt} \right) + \sum a_{qs} \frac{\int i_q \, dt}{C_q}, \quad (s=1, 2, \ldots n) \qquad (6)$$

The set of equations (6) is identical with the generalized Kirchhoff equations of electromotive force for the n circuits taken in the positive direction for the currents c_s, since the coefficients a_{qs} and a_{rs} provide the proper sign for each effective electromotive force occurring in these circuits and exclude all electromotive forces not occurring in the several circuits. The Kirchhoff laws and the above condition of stationary dissipation are therefore mutually equivalent.

In subsequent work it will be more convenient to merge the conditions of continuity in the equation of activity (4) than to use separate equations such as (5) to cover these conditions. This may be accomplished either by reducing the currents appearing in the equation of activity to a number equal to and so chosen as to correspond with the degrees of freedom of the network, or by adding fictitious currents which correspond to the significant branch points; *i.e.*, points, in excess of one in each connected part of the system, at which three or more branches meet. Their number being m, the number of branches (including each isolated closed circuit as a branch) being l, and the degrees of freedom being n, the relation holds, $n = l - m$.

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[*] To prove this rule let $f = m^{-1} F_m + n^{1} F_n$, (where F_m and F_n are homogeneous functions of $x, y, z, \ldots$ of order m and n) be given its stationary value, which requires $D_x f = D_y f = D_z f = \ldots = 0$. The sum of the differential coefficients multiplied in order by $x, y, z, \ldots$ consequently vanishes, that is,

$$x D_x f + y D_y f + z D_z f + \ldots = 0, \text{ or}$$

$$m^{-1} [x D_x F_m + y D_y F_m + \ldots] + n^{-1} [x D_x F_n + y D_y F_n + \ldots] = 0.$$

By the elementary property of homogeneous functions the bracketed expressions are equal to $m F_m$ and $n F_n$ so that the relation $F_m + F_n = 0$ is satisfied at the stationary value of f. This relation may be considered as a prescribed condition without having any effect on the final stationary result, but we could then eliminate F_m from the original expression for f and write $f = (n^{-1} - m^{-1}) F_n$, whence the stationary value of F_n, with the condition $F_m + F_n = 0$, corresponds to the unconditioned stationary value of f. The application in the paper is for $m = 1$, $n = 2$ and $f = F_1 + \frac{1}{2} F_2$.

The first transformation is accomplished by replacing the branch currents i_q in (**4**) by circuital currents such as c_s by the aid of such equations as (**5**). Rearranging the terms the form of the equation of activity may still be kept the same as in (**4**), but all quantities, e, i, R, L, M, C now refer to complete circuits and not to individual branches.

The second transformation follows from the identity of the condition of continuity for currents converging on branch point f,

$$\varphi_f = M_{f1}\, i_1 + M_{f2}\, i_2 + \ .\ .\ .\ M_{fr}\, i_r\ .\ .\ .\ + M_{fl}\, i_l = 0, \qquad (7)$$

$$M_{fr} = \pm 1 \text{ or } 0, \quad f = (l+1,\ .\ .\ .\ l+m),^*$$

with the condition that a fictitious circuit devoid of resistance, inductance, and capacity can experience no resultant electromotive force whatever be the currents flowing in the branches 1, 2, . . . r . . . l with which it has mutual inductances M_{f1}, M_{f2}, . . . M_{fr} . . . M_{fl}. This physical consideration shows that the conditions of continuity will be included in (**4**) by extending the summation to cover fictitious circuits devoid of resistance, etc., and with zero mutual inductances between each other and all real branches excepting only $M_{fr} = \pm 1$ when the real branch r terminates in the branch point f, the sign being positive or negative at the positive or negative end of the branch respectively.

To prove the same analytically we multiply each equation of (**7**) by i_f, take their sum, differentiate with respect to t and add this expression, which we may denote by

$$B = \frac{d}{dt} \sum i_f\, \varphi_f = \frac{d}{dt} \sum \sum M_{fr}\, i_f\, i_r$$

to (**4**), which is permissible since B must be equal to zero. On differentiating (**4**) (with multiplier $\frac{1}{2}$ added to $\Sigma R_q\, i_q^2$) with respect to the real current i_q, B introduces the new terms $\sum \frac{di_f}{dt}\, \frac{d\varphi_f}{di_q}$ to (**6**), and these are precisely the additional terms required by the conditions of continuity, since $\frac{di_f}{dt}$ plays the part of an undetermined multiplier. Again differentiation

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*These m fictitious circuits are numbered in sequence with the l real branches so as to make it possible to employ throughout the same notation for circuit constants and currents, *viz.*, R_f, i_f, etc.

with respect to the fictitious current i_f gives $\frac{d}{dt}\varphi_f=0$ or $\varphi_f=0$, the constant of integration being zero, as infinite energy in the fictitious circuits is to be excluded, and these are the equations of continuity (**7**). Thus after the addition of B, equation (**4**) includes all of the conditions of continuity.

It will be assumed in the subsequent work that the network under discussion has been transformed into a set of simple circuits, thus reducing the conditional equations to the equation of activity. The coefficients occurring in this equation and the number of currents entering it will depend upon the particular choice of simple circuits, but the general discussion of the network will be, to a considerable extent, independent of the choice of the simple circuit system. In concrete applications it will be advantageous, in order to have as few variables as possible, to use the first of the above transformations. In general work, however, the second transformation presents the distinct advantage of including all branches symmetrically.

General Equations for Cisoidal Oscillations

For cisoidal oscillations the preceding theorem may be given the following still simpler form:

The activity of the external sources of power which produce a steady cisoidal oscillation in any invariable network assumes the stationary value which is consistent with the conditions imposed by current continuity and the conservation of energy.

With cisoidal oscillations the differentiations and integrations indicated in the equation of activity (**4**) may be carried out and after dividing by the common factor e^{2ipt} and introducing the self and mutual impedances $Z_{qq}\,(=Z_q)$, $Z_{qr}\,(Z_{rq}=Z_{qr})$, the equation becomes

$$\sum_{q=1}^{q=n} E_q I_q = \sum_{q=1}^{q=n} Z_q I_q^2 + 2\sum_{r>q=1}^{q<r=n} Z_{qr} I_q I_r = \sum_{q=1}^{q=n}\sum_{r=1}^{r=n} Z_{qr} I_q I_r \qquad (8)$$

The left-hand and the right-hand sides of this equation are homogeneous functions of the first and second orders in terms of the currents. Comparison with the first and second order terms in (**4**) shows that the right-hand side of equation (**8**), which is the total power taken by the network, may be substituted in the general theorem for the power dissipated. Or, since the two sides of equation (**8**) are always equal, the left-hand side, which is the power supplied by the sources, may equally well be taken; whence the above theorem follows.

Stationary activity involves stationary driving point impedance and the theorem might be restated in terms of the impedances.

Differentiating equation (8) with respect to each of the n currents (after introducing the multiplier $\frac{1}{2}$ for the right-hand side) we have for the general equations determining the distribution of current:

$$\begin{aligned} &Z_{11}I_1+Z_{12}I_2\ldots\ldots\ldots\ldots+Z_{1n}I_n=E_1\\ &Z_{21}I_1+Z_{22}I_2\ldots\ldots\ldots\ldots+Z_{2n}I_n=E_2\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (9)\\ &Z_{n1}I_1+Z_{n2}I_2\ldots\ldots\ldots\ldots+Z_{nn}I_n=E_n \end{aligned}$$

The currents are therefore

$$I_q=\sum_{r=1}^{r=n}\frac{A_{qr}}{A}E_r$$

where A is the determinant of the impedances occurring as coefficients of the currents in (9) and $A_{qr}\ (=A_{rq})$ is the co-factor of Z_{qr} in this determinant. Substituting in equation (8), we find that the stationary power, that is the power which is actually expended on the network, is

$$P=\sum_{q=1}^{q=n}\sum_{r=1}^{r=n}\frac{A_{qr}}{A}E_qE_r=\frac{A_e-A}{A} \qquad (10)$$

where A_e differs from the determinant A only in having each element Z_{qr} augmented by E_qE_r.

Self- and mutual-admittances may be substituted for the self- and mutual impedances in the right-hand side of equation (8), the form of the expression being kept unchanged by simultaneously substituting potential differences for currents. The solution in terms of the admittances will then be obtained from a determinant in which the admittances enter precisely as do the impedances in "A". For certain problems, as will be readily seen, the admittance determinant is much more convenient than the impedance determinant. While the impedance determinant is made the special object of discussion in the remainder of this paper, it is to be understood that corresponding applications may be made of the admittance determinant.

THE DISCRIMINANT OF A NETWORK

The discriminant A of a network is defined as the determinant having the element Z_{qr} in the qth row and rth column; Z_{qr} being the mutual impedance between circuits q and r or the self-impedance of circuit q when $q=r$; the determinant to include the self- and mutual impedances of the system of simple circuits obtained by eliminating the branch points by closing each branch on itself and replacing each branch point, in excess of one in each connected part of the system, by a fictitious circuit of zero self-impedance connected by mutual impedances $+i$ and $-i$ to the several branches which have their positive or negative ends respectively at this branch point.

This will be taken as the normal form of the discriminant, since it is symmetrical in terms of all of the real branches and real closed circuits of the network. That it is also essentially symmetrical in all of the branch points follows from the fact that the value of the determinant is independent of the choice of the particular branch points to be excluded. The discriminant A is of fundamental importance in the discussion of the network because all effective impedances of the network may be determined directly from its array.

The degree of A in terms of the actual impedances of the network is equal to the number of degrees of freedom of the network, which is the same as the number of branches, reduced by the number of branch points, omitting one in each connected part of the system. The determinant A is of the first degree in each self-impedance, and of the second degree in each mutual impedance when physically considered, that is when the order of the subscripts is ignored ($Z_{rq} \equiv Z_{qr}$).

The co-factor of the product of the elements located at the intersection of rows $j, q, s, \ldots$ with columns $k, r, t \ldots$ respectively of determinant A will be denoted by $A_{jk.qr.st} \ldots = A_\alpha'$, where α stands for the paired list $j\,k\,.\,q\,r\,.\,s\,t \ldots$ Thus A has the value $A_\alpha Z_{jk} Z_{qr} Z_{st} \ldots$ in case all other elements in rows $j, q, s, \ldots$ and columns $k, r, t, \ldots$ are replaced by zero; the arithmetical value of the co-factor depends only on the choice of rows $j, q, s, \ldots$ and columns $k, r, t \ldots$ which occur in the subscript; its algebraical sign depends upon the sequence of the rows and columns and is changed by each inversion of rows or columns. It follows that if the same row or column occurs twice in the subscript the value of the co-factor is zero. Where we have occasion to restore one or more rows and an equal number of columns of A to A_α, the elements to be removed from α will be indicated as a divisor of the subscript α. The algebraical value of the expression $A_{\frac{\alpha}{\beta}}$ is uniquely and completely determined by canceling the denominator against a part or the whole of the numerator, making inversions, if necessary, in the numerator or denominator; in case the denominator cannot be entirely eliminated by this process the symbol indicates a determinant with identical rows or columns, and it is therefore equal to zero. For example:

$$A_{\frac{11\cdot22}{12}}=-A_{\frac{12\cdot21}{12}}=-A_{21},\quad A_{12\cdot13}=0,\quad A_{\frac{12\cdot23}{34}}=0,\quad A_{\frac{11\cdot22}{12\cdot21}}=-A$$

$$\text{and } A_{jk.qr.st}\dots=\frac{D_{Z_{jk}}D_{Z_{qr}}D_{Z_{st}}\cdots A}{2^{(\delta_{jk}+\delta_{qr}+\delta_{st}\,\dots\,)}},\tag{11}$$

$$Z_{rq}\equiv Z_{qr}\not\equiv 0,\qquad \delta_{qr}=\begin{cases}0 \text{ if } q=r\\ 1 \text{ if } q\neq r\end{cases}$$

where the differentiations correspond to actual physical variations in the impedances and therefore treat mutual impedances with interchanged subscripts as identical.

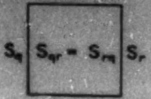
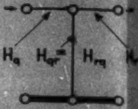
By applying the following rules the expanded expressions for A and its co-factors may be written down directly from the simple circuit system replacing the network, without reference to the determinant. This method of expansion is often more convenient than the use of the ordinary rules for expanding the determinant.

A is the sum of all possible products in which each circuit is represented either by its self-impedance or by its mutual impedance to another circuit, the mutual impedances occurring, however, in closed cycles of two or more constituents only, so that the subscripts may be written $k\,m$, $m\,q$, $q\,u$, . . . $w\,k$, each cycle introducing the sign-factor + or − according as the cycle contains an odd or an even number of terms; each cycle of three or more circuits also introducing the factor 2 to care for the alternative way of associating the mutual impedances and the circuits of the cycle.

A_{qq} is the coefficient of Z_{qq} in A, *i.e.*, A_{qq} is the value taken by A when circuit q is removed from the network.

A_{qr} is the coefficient of Z_{qr} *after* writing A in symmetrical form with respect to Z_{qr} and Z_{rq}, *i.e.*, A_{qr} is the value taken by $A \div Z_{qr}$ if circuit q is represented in each product by the mutual impedance Z_{qr}.

EFFECTIVE IMPEDANCES OF EQUIVALENT NETWORKS WITH T

	FIG. 1.  	FIG. 2. 
$S_q =$	$\frac{A}{A_{qq}}$	$\frac{H_qH_r+H_qH_{qr}+H_rH_{qr}}{H_r+H_{qr}}$
$S_r =$	$\frac{A}{A_{rr}}$	$\frac{H_qH_r+H_qH_{qr}+H_rH_{qr}}{H_q+H_{qr}}$
$S_{qr} =$	$\frac{A}{A_{qr}}$	$\frac{H_qH_r+H_qH_{qr}+H_rH_{qr}}{H_{qr}}$
$H_q =$	$\frac{S_qS_{qr}(S_{qr}-S_r)}{S^2_{qr}-S_qS_r}$	$\frac{A_{rr}-A_{qr}}{A_{qq\cdot rr}}$
$H_r =$	$\frac{S_rS_{qr}(S_{qr}-S_q)}{S_{qr}^2-S_qS_r}$	$\frac{A_{qq}-A_{qr}}{A_{qq\cdot rr}}$
$H_{qr} =$	$\frac{S_qS_rS_{qr}}{S_{qr}^2-S_qS_r}$	$\frac{A_{qr}}{A_{qq\cdot rr}}$
$U_q =$	$-\frac{S_qS_{qr}}{S_q-S_{qr}}$	$\frac{H_qH_r+H_qH_{qr}+H_rH_{qr}}{H_r}$
$U_r =$	$-\frac{S_rS_{qr}}{S_r-S_{qr}}$	$\frac{H_qH_r+H_qH_{qr}+H_rH_{qr}}{H_q}$
$U_{qr} =$	S_{qr}	$\frac{H_qH_r+H_qH_{qr}+H_rH_{qr}}{H_{qr}}$
$J_q =$	$\frac{S_qS_{qr}^2}{S_{qr}^2-S_qS_r}$	H_q+H_{qr}
$J_r =$	$\frac{S_rS_{qr}^2}{S_{qr}^2-S_qS_r}$	H_r+H_{qr}
$J_{qr} =$	$-\frac{S_qS_rS_{qr}}{S_{qr}^2-S_qS_r}$	$-H_{qr}$
$K_q =$	$\sqrt{\frac{S_qS_rS_{qr}^2}{S_{qr}^2-S_qS_r}+\left[\frac{(S_q-S_{qr})\,S_{qr}^2}{2(S_{qr}^2-S_qS_r)}\right]^2}+\frac{(S_q-S_r)\,S_{qr}^2}{2(S_{qr}^2-S_qS_r)}$	$\sqrt{\frac{(H_q+H_r)(H_q+H_r+4H_{qr})}{4}}+\frac{H_q-H}{2}$
$K_r =$	$\sqrt{\frac{S_qS_rS_{qr}^2}{S_{qr}^2-S_qS_r}+\left[\frac{(S_q-S_r)\,S_{qr}^2}{2(S_{qr}-S_qS_r)}\right]^2}-\frac{(S_q-S_r)\,S_{qr}^2}{2(S_{qr}^2-S_qS_r)}$	$\sqrt{\frac{(H_q+H_r)(H_q+H_r+4H_{qr})}{4}}-\frac{H_q-}{2}$
$\Gamma_{qr} =$	$\cosh^{-1}\frac{S_{qr}(S_q+S_r)}{2S_qS_r}$	$\cosh^{-1}\frac{H_q+H_r+2H_{qr}}{2H_{qr}}$

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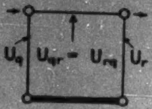
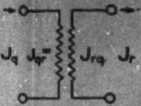
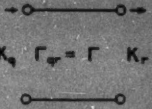
CIRCUITS, IN TERMS OF EACH OTHER AND OF THE DETERMINANT A.

FIG. 3.	FIG. 4.	FIG. 5.
		
	$\frac{J_qJ_r-J_{qr}^2}{J_r}$	$\frac{2K_qK_r}{(K_q+K_r)\coth\Gamma+(K_r-K_q)}$
	$\frac{J_qJ_r-J_{qr}^2}{J_q}$	$\frac{2K_qK_r}{(K_q+K_r)\coth\Gamma-(K_r-K_q)}$
	$-\frac{J_qJ_r-J_{qr}^2}{J_{qr}}$	$\frac{2K_qK_r}{K_q+K_r}\sinh\Gamma$
	J_q+J_{qr}	$\frac{K_q+K_r}{2}\tanh\frac{\Gamma}{2}+\frac{K_q-K_r}{2}$
	J_r+J_{qr}	$\frac{K_q+K_r}{2}\tanh\frac{\Gamma}{2}-\frac{K_q-K_r}{2}$
	$-J_{qr}$	$\frac{K_q+K_r}{2\sinh\Gamma}$
	$\frac{J_qJ_r-J_{qr}^2}{J_r+J_{qr}}$	$\frac{2K_qK_r}{(K_q+K_r)\tanh\frac{\Gamma}{2}+(K_r-K_q}$
	$\frac{J_qJ_r-J_{qr}^2}{J_q+J_{qr}}$	$\frac{2K_qK_r}{(K_q+K_r)\tanh\frac{\Gamma}{2}-(K_r-K_q}$
	$-\frac{J_qJ_r-J_{qr}^2}{J_{qr}}$	$\frac{2K_qK_r}{K_q+K_r}\sinh\Gamma$
	$\frac{A_{rr}}{A_{qq\cdot rr}}$	$\frac{K_q+K_r}{2}\coth\Gamma+\frac{K_q-K_r}{2}$
	$\frac{A_{qq}}{A_{qq\cdot rr}}$	$\frac{K_q+K_r}{2}\coth\Gamma-\frac{K_q-K_r}{2}$
	$-\frac{A_{qr}}{A_{qq\cdot rr}}$	$-\frac{K_q+K_r}{2\sinh\Gamma}$
$\frac{(U_qU_{qr}+U_rU_{qr}+4U_qU_r)+U_q-U_r)U_{qr}}{2(U_q+U_r+U_{qr})}$	$\sqrt{\left(\frac{J_q+J_r}{2}\right)^2-J_{qr}^2}+\frac{J_q-J_r}{2}$	$\sqrt{\frac{A}{A_{qq\cdot rr}}+\left(\frac{A_{rr}-A_{qq}}{2\ A_{qq\cdot rr}}\right)^2}+\frac{A}{2}$
$\frac{(U_qU_{qr}+U_rU_{qr}+4U_qU_r)-(U_q-U_r)U_{qr}}{2(U_q+U_r+U_{qr})}$	$\sqrt{\left(\frac{J_q+J_r}{2}\right)^2-J_{qr}^2}-\frac{J_q-J_r}{2}$	$\sqrt{\frac{A}{A_{qq\cdot rr}}+\left(\frac{A_{rr}-A_{qq}}{2\ A_{qq\cdot rr}}\right)^2}-\frac{A}{2}$
$\frac{+U_r)U_{qr}}{2U_qU_r}\Big)$	$\cosh^{-1}\frac{-(J_q+J_r)}{2J_{qr}}$	$\cosh^{-1}\frac{A_{qq}+A_{rr}}{2A_{qr}}$

EFFECTIVE IMPEDANCES OF ANY NETWORK

In the theoretical discussion of networks we are concerned not so much with particular values of the electromotive forces and currents, as with their relative values. For this reason the impedances, which are the ratios of electromotive forces to currents, and the attenuation factors, which are either the ratios of currents to each other, or of electromotive forces to each other, are chosen as the immediate objects of investigation.

Effective impedances may be defined in various ways, for example as:

$$(a)\quad \frac{\text{potential of point } s_j \text{ minus potential of point } s_k}{\text{current at point } s_l},$$

$$(b)\quad \delta\,\frac{\text{power taken by any part } S_o \text{ of network}}{\text{product of currents at points } s_q \text{ and } s_r},$$

($\delta = 1$ or $\frac{1}{2}$ for self and mutual impedances respectively.)

$$(c)\quad \frac{1}{\delta}\,\frac{\text{product of potential differences points } s_t,\ s_u \text{ and } s_v,\ s_w}{\text{power taken by any part } S_x \text{ of network}}$$

($\delta = 1$ or $\frac{1}{2}$ for self- and mutual impedances respectively.)

(*d*) The impedances required to make a normal type of network of the requisite number of parameters equivalent to the given network under specified conditions of operation.

As examples of the above definitions we may instance the following:

The mutual impedance of a transformer is the ratio, with sign reversed, of the electromotive force induced in either winding to the inducing current flowing in the other winding, which falls under definition (*a*) if the secondary is first open-circuited.

In discussing below the power taken by the actual resistances in a network use is made of definition (*b*) in formula (**26**).

The expression, formula (**10**), for the total power taken by a network in terms of the impressed forces, gives, on breaking up the expression into its individual terms, a set of self-impedances and mutual impedances defined in accordance with definition (*c*).

As an example of definition (*d*) we may take the important case where we are concerned only with two accessible circuits in a network and wish to replace the given network by a normal type having only the required three complex parameters. The normal networks which are ordinarily employed are the " T ", the " Π," the transformer and the artificial line and for these the effective impedances are given in table I, together with the simple circuit impedances which equal the driving point impedance in either circuit S_q and S_r and the driving-driven point impedance S_{qr} of a single circuit which would give the electromotive force ÷ current ratio actually obtaining when the electromotive force is inserted in q (or r) and the current is measured in r (or q). J_q, J_r, J_{qr} are called the primary, secondary and mutual impedances as they correspond to the primary self-inductance, secondary self-inductance, and mutual inductance following established scientific usage. This terminology is employed throughout this paper, as its extension to three or more circuits is obvious and symmetrical, and it seems to be the only logical system. Many electrical engineers, however, call H_q, H_r, H_{qr}^{-1} (H_{qr} being taken with inductive reactance) the primary impedance, secondary impedance and primary admittance, in case the assumed ratio of turns is 1 to 1.

The table refers to the general case where the two circuits are not symmetrical, but the formulæ are in such form as to facilitate reduction to the special case of symmetrical circuits. In this table different letters are employed for the various effective impedances thus somewhat reducing the multiplication of subscripts.

ELIMINATION OF CONCEALED CIRCUITS

In general we may divide a network into a concealed and an accessible part and it is convenient to eliminate the former from explicit appearance in the impedance determinant A when we are concerned only with the effects which are produced in the accessible part of the network due to causes which are likewise confined to this part of the network.

Elimination of a group of concealed circuits (or of any circuits which contain no impressed forces) from explicit appearance in A is equivalent to the substitution of new effective impedances

$$J_{qr} = \frac{A_{\frac{\alpha}{qr}}}{A_{\alpha}}$$

between accessible circuits q and r where α stands for the product of the original self-impedances of the accessible circuits.

To prove this we notice that the set of Kirchhoff electromotive force equations for the concealed circuits taken alone give

$$I_c = \frac{1}{A_a} \sum_r I_r A_{\frac{a.xc}{xr}} \qquad \text{where} \begin{cases} c = \text{any concealed circuit} \\ r = \text{any accessible circuit} \\ x = \text{any circuit} \end{cases}$$

which substituted in the electromotive force equation for any accessible circuit q make the new coefficient of I_r in this equation

$$J_{qr} = Z_{qr} + \frac{1}{A_a} \sum_c Z_{qc} A_{\frac{a.qc}{qr}} = \frac{1}{A_a} \left[Z_{qr} A_{\left(\frac{a}{qr}\right)qr} + \sum_c Z_{qc} A_{\left(\frac{a}{qr}\right)qc} \right]$$

after setting $x = q$

$$= \frac{A_{\frac{a}{qr}}}{A_a} = \frac{A_{\frac{a}{rq}}}{A_a} = J_{rq}, \text{ as } A \text{ is symmetrical.} \tag{12}$$

J_{qr} is thus the new effective mutual impedance (or self-impedance if $q = r$) between accessible circuits q and r.

In the important case where all but two of the circuits are eliminated, we have

$$J_{qq} = \frac{A_{rr}}{A_{qq \cdot rr}}$$

$$J_{rr} = \frac{A_{qq}}{A_{qq \cdot rr}} \tag{13}$$

$$J_{qr} = \frac{-A_{qr}}{A_{qq \cdot rr}}$$

And if but one circuit q is regarded as accessible, the driving point impedance of the network to an electromotive force inserted in that circuit, is

$$J_{qq} = \frac{A}{A_{qq}} \tag{14}$$

If we eliminate the circuits corresponding to all of the branch points and to an equal number of the branches which are connected to these branch points but do not form any closed circuit among themselves, it may be shown that: $A_a = 1$; the new effective impedances are equal to sums and differences of the original impedances with coefficients which are 0, ±1, or ±2; the circuits which are not eliminated are equal in number to the degrees of freedom of the network. The case falls under that directly derived above by the use of circuital currents.

If $A_a=0$ the method of elimination fails, which shows that whenever fictitious branch point circuits are eliminated at least one branch connected to each branch point must be included and that the number of closed circuits formed by the branches must not be greater than the excess of eliminated branches over eliminated branch points.

No change is made in the effective self- or mutual impedance of an accessible circuit q by the elimination of circuits which have no mutual impedance with circuit q. That is $A_{\frac{a}{qr}}=Z_{qr}A_a$ since the added q row has but one term Z_{qr} which differs from zero.

A concealed branch of admittance Y which is free from mutual impedances may be eliminated by adding Y to each of the two self-impedances and subtracting Y from the mutual impedance of the two fictitious circuits which replace the terminal branch points of the concealed branch. Any number of concealed branches may be eliminated in this way; the total self-impedance added to any fictitious circuit will equal the total admittance of the eliminated branches terminating at the corresponding branch point; the total mutual impedance subtracted between any two fictitious circuits will equal the total admittance eliminated between the corresponding branch points.

To prove, let the concealed branch impedance be $Z=1\div Y=A_a$, then, if the self- and mutual-impedances of the fictitious circuits corresponding to the terminals of this branch are originally Z_1, Z_2 and Z_{12}, they become after the elimination of the concealed branch

$$J_1=\frac{A_{\frac{a}{11}}}{A_a}=Y\begin{vmatrix} Z_1 & \pm i \\ \pm i & Z \end{vmatrix}=Z_1+Y$$

$$J_2=\frac{A_{\frac{a}{22}}}{A_a}=Y\begin{vmatrix} Z_2 & \mp i \\ \mp i & Z \end{vmatrix}=Z_2+Y$$

$$J_{12}=\frac{A_{\frac{a}{12}}}{A_a}=Y\begin{vmatrix} Z_{12} & \pm i \\ \mp i & Z \end{vmatrix}=Z_{12}-Y$$

Any concealed part of a network connected to the remainder of the network through a group of terminals (*branch points*) *q, r, s, . . only* (and having the impedance determinant A_α or A_β according as the concealed part is taken alone or is taken together with the circuits corresponding to the group of accessible terminals) *may be replaced by any one of the following:*

(*a*) Self-impedances $A_{\frac{\alpha}{qq}} \div A_\alpha$ and mutual impedances $A_{\frac{\alpha}{qr}} \div A_\alpha$ added to the fictitious circuits corresponding to the group of terminals.

(*b*) Branches, devoid of mutual impedance, connecting the group of terminals in pairs and having the admittances $-A_{\frac{\alpha}{qr}} \div A_\alpha$. These admittances we will call the equivalent direct admittances of the network.

(*c*) Branches radiating from a common concealed point, one to each of the terminals, with self-impedances $A_{\beta.qq} \div A_\beta$ and mutual impedances $A_{\beta.qr} \div A_\beta$.

(*d*) Branches radiating from a common concealed point, one to each of the group of terminals, these branches being devoid of self-impedance and having mutual impedances $-(A_{\beta.qq} + A_{\beta.rr} - 2\,A_{\beta.qr}) \div 2\,A_\beta$.

(*e*) Branches connecting any one of the terminals *q* to each of the remaining accessible terminals *r, s,* . . . . , the branch connected to terminal *r* having the self-impedance $(A_{\beta.qq} + A_{\beta.rr} - 2\,A_{\beta.qr}) \div A_\beta$ and the mutual impedance $(A_{\beta.qq} + A_{\beta.rs} - A_{\beta.qr} - A_{\beta.qs}) \div A_\beta$ to the branch connected to terminal *s*.

Substitution (*a*) is a restatement of the results previously established for the case of concealed and accessible parts which are not connected the one to the other by mutual impedances.

To show that (*b*) is equivalent to (*a*) apply to (*b*) the theorem for eliminating concealed branches which are devoid of mutual impedances; the fictitious circuits corresponding to the group of terminals will thereby have their mutual impedances increased by $A_{\frac{\alpha}{qr}} \div A_\alpha$ and their self-impedances increased by

$$-\frac{1}{A_\alpha}\sum_{r\,(\neq q)} A_{\frac{\alpha}{qr}} = \frac{1}{A_\alpha}\left(A_{\frac{\alpha}{qq}} - \sum_{r} A_{\frac{\alpha}{qr}}\right) = A_{\frac{\alpha}{qq}} \div A_\alpha$$

since the complete summation with respect to *r* of the bordered determinants $A_{\frac{\alpha}{qr}}$ equals the determinant A_α bordered by the row q and a column equal to the sum of all of the fictitious circuit columns r, and vanishes since terms $+i$ and $-i$ occur in pairs and cancel, making the column identically equal to zero. Substitution (*b*) having been transformed into substitution (*a*) the two are mutually equivalent.

Substitutions (*c*), (*d*) and (*e*) are readily shown to be mutually equivalent to each other and to the original network by showing that the impedance between any two terminals u and v with all others insulated is $(A_{\beta.uu}+A_{\beta.vv}-2A_{\beta.uv})\div A_{\beta}$.

The direct admittance between two terminals of any network, as defined under (*b*), is equal to one-half of the excess of the grounded admittance of the two terminals taken separately over their grounded admittance when taken together as a single terminal. By the grounded admittance of a terminal is understood the admittance between that terminal and ground with all of the other terminals grounded. As grounded admittance can be readily measured with simple apparatus, this always affords one method of experimentally determining the direct admittance in any network.

COMPLETE ELIMINATION OF EITHER MUTUAL IMPEDANCES OR SELF-IMPEDANCES

It has been shown [(*b*) and (*d*) above] that if we retain a group of terminals as the only accessible part, any network may be replaced either by a set of direct impedances connecting the terminals in pairs, or by a set of mutual impedances between branches radiating from a common point and terminating one at each of the terminals. In the first case all mutual impedances are avoided; in the second case all self-impedances are avoided. Applications to the simple transformer are of interest as showing that in these substitutions an open circuit is taken care of either by parallel self-impedances which are equal but of opposite signs or by infinite mutual impedances differing by finite amounts. The substitutions show that a transformer J_1, J_2, J_{12}, is equivalent to either

(*a*) The six-branch network directly connecting the four terminals, the impedances of which are

$$\frac{J_1 J_2 - J_{12}^2}{J_2},\ \frac{J_1 J_2 - J_{12}^2}{J_1},\ \frac{J_1 J_2 - J_{12}^2}{J_{12}},\ -\frac{J_1 J_2 - J_{12}^2}{J_{12}} \qquad (15)$$

between the primary terminals, the secondary terminals, each of the two pairs of correspondingly poled terminals of primary and secondary and each of the two pairs of non-corresponding terminals of primary and secondary, respectively. (In Figs. 6 and 7 terminals 1-2, 3-4, 1-3, and 2-4, 1-4 and 2-3 respectively.)

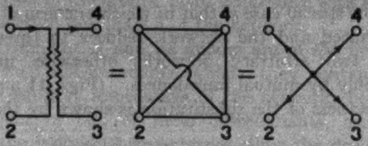


FIG. 6 FIG. 7 FIG. 8

Transformer and equivalent networks having four accessible terminals

Or (*b*) the four-branch network connecting the four terminals to a concealed common point, the mutual impedances being

$$-\frac{J_1}{2}, -\frac{J_2}{2}, \infty + \frac{J_{12}}{4}, \infty - \frac{J_{12}}{4} \tag{16}$$

between the branches (taken with their positive directions diverging from the common point) which terminate at the same pairs of terminals as for case (*a*), respectively. See Figs. 6 and 8.

In certain cases a mutual impedance may be eliminated by properly augmenting the impedances of not more than four branches, without altering the arrangement of branches in any way or imposing any restriction as to whether they are concealed or accessible. These cases are all included under that of mutual impedance between diagonally opposite branches of a generalized bridge, by which we will understand a network differing from the ordinary bridge only in having the four bridge corners replaced

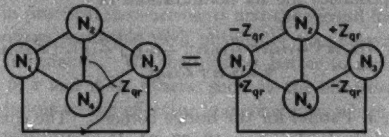
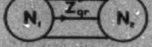


FIG. 9 FIG. 10

Generalized bridge with equivalent mutual and self impedances

by four arbitrary networks; these corner networks may have mutual impedances between one another, but the only branches connecting them are to be the six branches corresponding to the simple bridge. *Mutual impedance between diagonally opposite branches in the generalized bridge is replaceable by an equal amount* *of self-impedance in each of the four bridge-arms, added to or subtracted from the original self-impedance of the arm, according as the arm connects the branches having the mutual impedance with their positive directions concurrent or opposed.* (Figs. 9 and 10.) An important special case is that in which one arm of the bridge is open-circuited and the network reduces to three branches connecting two arbitrary networks otherwise unconnected except possibly by mutual impedances. (Figs. 11 and 12.)

The correctness of the substitution is shown by the fact that



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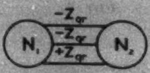

FIG. 11 FIG. 12

Three-branch connection with equivalent mutual and self impedances

the impedance of every closed circuit is the same before and after the substitution, and that this is the most general case is proven by noticing: (1), that the generalized bridge becomes an unrestricted network by admitting any number of branches connecting the four corner networks in pairs; and (2), that with a single branch added to Figs. 9 and 10, it is impossible to keep the self-impedance of every closed circuit the same in the two cases, for the added branch requires different increments according to the circuit through which it is closed.

In the simple bridge circuit there are 15 possible mutual impedances which may be eliminated by taking as the effective branch impedances the six permutations of

$$Z_{12}'=Z_{12}+Z_{12,23}+Z_{12,24}+Z_{12,31}+Z_{12,41}+Z_{13,14}+Z_{23,24}+Z_{13,42}+Z_{14,32} \tag{17}$$

where 1, 2, 3, 4 stand for the bridge corners. The condition for a balance of the bridge arms 12, 23, 34, 41 is therefore always

$$Z_{12}'\,Z_{34}'=Z_{23}'\,Z_{41}' \tag{18}$$

IMPEDANCE LOCI

It is often of importance to know how the impedances of a network will vary if the self-impedances or mutual impedances of one or more of the branches of the network are varied over lines or areas in any physically possible manner. On account of the magnitude of this subject we shall touch on the simplest case only, namely that of the driving point impedance with a variable impedance added to one branch of the network.

As the discriminant A and its minors are of the first degree in terms of each self-impedance which they contain, it follows that the effective impedances of the network, being equal to the quotient of two of these determinants, are bilinear functions of the individual impedances; thus the driving point impedance of a network at circuit q is connected with a self-impedance Z inserted in any circuit r by a relation of the form

$$S_q = \frac{a\,Z+b}{c\,Z+d} \tag{20}$$

where a, b, c and d are constants.

The property of the bilinear transformation which is of special importance to us is that it transforms circles into circles, that is, if Z be regarded as a variable and be made to traverse any circle whatsoever, the driving point impedance S will also describe a circle. In making this statement the straight line is included as the limit of a circle so that the loci of S and Z may be straight lines as well as circles. This property of the bilinear transformation is discussed at length in the theory of analytic functions and need not be entered into here.

We are especially concerned with the cases where the locus of Z is a straight line such as the axis of reals or the axis of imaginaries, because the first is a variation which it is convenient to make use of in practical measurements and the second forms the extreme boundary realizable with physically possible values of the inserted impedance. We shall find it better to replace the constants a, b, c and d by others, such as the effective transformer impedances or the effective line constants, which have a physical significance.

A network having effective transformer constants J_1, J_2, J_{12} *effects the transformation of the half of the* Z*—plane on the positive side of the reactance axis into the area bounded by a circle with center at* Z_i *and radius* R_i*:*

$$Z_i = J_1 - \frac{J_{12}^2}{J_2+J_2'}, \qquad R_i = \frac{|J_{12}^2|}{J_2+J_2'} \tag{21}$$

the axis of reals going over into the circumference of a circle having its center at Z_r *and radius* R_r:

$$Z_r = J_1 - \frac{J_{12}^2}{J_2 - J_2'}, \qquad R_r = \frac{|J_{12}^2|}{|J_2 - J_2'|} \tag{22}$$

where J_2' *is the conjugate of* J_2 *and* $|J_{12}^2|$ *the modulus of* J_{12}^2. *The two circles cut each other orthogonally at* J_1 *and* $(J_1 - J_{12}^2 \div J_2)$ *which correspond to open and short-circuited secondary. The double points = effective line impedances (far end with sign reversed) are*

$$\left.\begin{matrix} K_1 \\ -K_2 \end{matrix}\right\} = \frac{J_1 - J_2}{2} \pm \tfrac{1}{2}\sqrt{(J_1 + J_2)^2 - 4J_{12}^2} \tag{23}$$

Proof: Close the secondary through the added impedance Zx, where x is a real variable, and the effective driving point impedance at the primary is

$$S_1 = \frac{J_1(J_2 + Zx) - J_{12}^2}{J_2 + Zx} = J_1 - \frac{J_{12}^2}{J_2 + Zx} \; \frac{Z'(J_2 + Zx) - Z(J_2' + Z'x)}{J_2 Z' - J_2' Z} \tag{24}$$

$$= \left(J_1 - \frac{J_{12}^2 Z'}{J_2 Z' - J_2' Z}\right) + \left(\frac{J_{12}^2 Z}{J_2 Z' - J_2' Z}\right)\left(\frac{J_2' + Z'x}{J_2 + Zx}\right) \tag{25}$$

and in this form the expression obviously represents a circle, of which the center is the first term, and the radius the modulus of the last term, since the variable x occurs only in the last factor of the last term and variations in x change the angle but not the modulus of this factor as its numerator is the conjugate of its denominator. If $Z = -Z' = i$, the inserted impedance is pure imaginary and we obtain from (**25**) the constants for the boundary circle as given in (**21**). If $Z = Z' = 1$, the added impedance is real and the effective driving point impedance falls on a circle with the constants as given in (**22**). To determine the double points substitute $Zx = S = K$ in the first part of (**24**) and solve the resulting quadratic in K which gives the values (**23**).

As a practical example of impedance loci, consider Fig. 13, which shows the driving point impedance of a transmission line for a frequency of 1,300 cycles per second, the line containing 6.201 wave lengths, presenting an attenuation constant of 0.9123 and having line impedances $K_1 = 1762 - 191i$ and $K_2 = 1614 - 781i$ for transmission from the driving point to the receiving end and vice versa. The driving point impedances actually measured are the points marked by circles near *a*, *b*, *c* and *d* for which the far end of the line was closed through a short circuit,

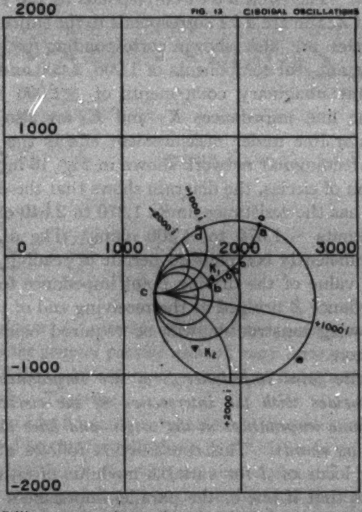

FIG. 13.—Bilinear transformation for a line containing 6.201 wave lengths and having the attenuation constant 0.9123 and the line impedances $K_1 = 1762 - 191\,i$ and $K_2 = 1614 - 781i$ which maps the half plane on the positive side of the imaginary axis into the circle *a d c e* with the rectangular ruling mapping into the orthogonal system of circles.

through 2,000 ohms, through an open circuit and through a capacity of 0.107 mf. respectively. As but three measurements are necessary in order to completely determine the three bilinear constants, it was necessary to adjust the four observations to the most probable bilinear transformation. It will be seen that the corrections which it was necessary to apply to the observations were small, being in fact well within the errors of observation. The circle *a d c e* corresponds to the entire imaginary axis of Z; the arc *a b c* corresponds to the entire positive axis of Z. Circles are also shown corresponding to values of Z having constant real components of 1,000, 2,000 and 3,000 ohms and constant imaginary components of $\pm 1{,}000$ and $\pm 2{,}000$ ohms. The line impedances K_1 and K_2 are also shown. As the particular line under measurement effects the transformation of the rectangular network shown in Fig. 13 into the orthogonal system of circles, the diagram shows that the driving point impedance has the resistance limits 1,270 to 2,640 ohms and the reactance limits $-1{,}070$ to $+300$ ohms. The diagram as it stands is sufficiently complete to permit of reading off approximately the value of the driving point impedance for any value of the impedance Z bridged at the receiving end of the line.

The following construction will be required below and may be proven here.

The effective joint impedance S of two impedances Z_1, Z_2 in parallel coincides with the intersection of the circles which are tangent to these impedances at the origin and have the individual impedances as chords. This construction follows at once from the circular locus of S for variable modulus of either Z_1 or Z_2 and the fact that if one of the parallel impedances Z_1 vanishes or the other impedance Z_2 becomes infinite the joint impedance is equal to Z_1. This construction is employed in Fig. 15 for obtaining S from Z_1 and Z_2 or vice versa.

DIVISION OF POWER BETWEEN THE RESISTANCES AND REACTANCES OF A NETWORK

The total power taken by a network is the sum of the powers taken by the individual self-impedances and mutual impedances, and to determine the division of this power between parts of the network it is merely necessary to find the summations for each part separately. As the total power and all of its components are directly proportional to the square of the current entering the network at the driving point, it is more convenient to consider, as the immediate object of discussion, the effective impedances which are defined as the ratios of the powers to the driving current squared. Accordingly we shall discuss the effective impedances S, U, $V\,i$ which correspond respectively to the total powers taken by the entire network, by the true resistances alone, and by the reactances alone. From this definition of these impedances it follows that

$$S = U + Vi = \sum_{j=1}^{n} \sum_{k=1}^{n} Z_{jk} \frac{I_j I_k}{I_d^2} = \sum_{j=1}^{n} Z_j \left(\frac{I_j}{I_d}\right)^2 + 2 \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} Z_{jk} \frac{I_j I_k}{I_d^2},$$

$$U = \sum_{j=1}^{n} \sum_{k=1}^{n} R_{jk} \frac{I_j I_k}{I_d^2}, \qquad \text{where } Z_{jk} = R_{jk} + i\,X_{jk} \tag{26}$$

$$Vi = i \sum_{j=1}^{n} \sum_{k=1}^{n} X_{jk} \frac{I_j I_k}{I_d^2}.$$

The impedance U corresponding to the power taken by the resistances in the general passive network may have any argument, and any modulus which is not greater than the effective resistance of the network. To prove:

Consider an ideal line of zero attenuation containing s wave lengths, closed at the far end through a resistance equal in value to the line impedance K, with an impedance $(R-K)+Bi$ in series at the sending end so as to make the total impedance at the sending end equal to $R+Bi$. A current I flowing at the sending end gives rise to a current I cis $(-2\pi s)$ at the receiving end so that the total power taken by the resistances is

$$P = (R-K)\,I^2 + K\,I^2 \operatorname{cis}(-4\pi s)$$

Therefore

$$U = (R-K) + K \operatorname{cis}(-4\pi s)$$

an impedance which may obviously assume any argument and any modulus not exceeding R with positive real values of K, $(R-K)$, and s.

The modulus of U can under no circumstances be greater than the effective resistance of the network for if this were the case the correlated sinusoidal oscillation would have, at some part of each oscillation, a negative total consumption of power by the resistances which is obviously impossible when the network contains neither sources of power nor so-called negative resistances, which are excluded throughout this discussion.

In Fig. 14 S and R represent the effective driving point impedance and the effective driving point resistance of the network, while U and Vi show a possible resolution of the impedance S into components corresponding to the powers taken by the true resistances and the reactances respectively. The circle $R\,b\,c\,d$ drawn about the origin with $O\,R$ as a radius is the maximum possible locus of U. If U falls at point b or d the power taken by the reactances has its maximum or its minimum value. If U falls at R the power taken by the reactances is 90 degrees ahead of the power taken by the resistances and this case corresponds to the series arrangement of a resistance and a reactance. (This is for positive reactance; with negative reactance the lead becomes a 90 degree lag.) At point c the relative phases are reversed, the resistances taking power 90 degrees in advance of that taken by the reactances; this case, as follows from the formulæ deduced below for parallel circuits, may be realized theoretically by the association of a pure resistance and a pure positive reactance in parallel. The point of special interest is the origin O; if U vanishes the cisoidal powers taken by the various resistances cancel each other in the summation for the resultant; in the correlated sinusoidal oscillation the power taken by the resistances is constant, that is the total generation of heat in the network does not fluctuate during an oscillation. This would seem to be a property which might have practical application.

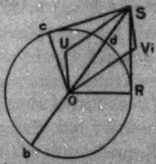

FIG. 14.—Resolution of the driving point impedance S into the impedances corresponding to the power taken by the resistances (U) and by the reactances ($V\,i$); $R\,b\,c$ is the extreme boundary for U.

If λ_1, λ_2, *are the maximum and minimum driving point impedance arguments obtainable from the elements employed in a network of driving point impedance* $S=R+Xi=|S|\text{cis}\,\sigma$ *the impedance* U *must lie in the lenticular area common to the two circles which intersect at the effective resistance of the network* (R) *and are centered at the projections of* S *on lines drawn through the origin at the angles* $(\sigma-\lambda_1)$ *and* $(\sigma-\lambda_2)$.

Multiply each impedance Z_{jk} in the network by cis $\left(\frac{\pi}{2}-\lambda\right)$. As this leaves the current ratios unchanged the new value of U will be

$$\underline{U}=\sum\sum|Z_{jk}|\cos\left(\frac{\pi}{2}-\lambda+\sigma_{jk}\right)\frac{I_jI_k}{I_d^2}$$

$$=i\cos\lambda\sum\sum|Z_{jk}|\text{ cis }\sigma_{jk}\frac{I_jI_k}{I_d^2}$$

$$-i\text{ cis }\lambda\sum\sum|Z_{jk}|\cos\sigma_{jk}\frac{I_jI_k}{I_d^2}$$

$$=i\,S\cos\lambda-i\,U\text{ cis }\lambda$$

Therefore $\quad U=i\,\underline{U}\text{ cis }(-\lambda)+S\cos\lambda\text{ cis }(-\lambda)$

which expresses the actual value of U in terms of the modified value $\underline{U}$. We may make $\lambda=\lambda_1$ without introducing any resultant negative resistance in the network, for the multiplication of each impedance by cis $\left(\frac{\pi}{2}-\lambda_1\right)$ raises the maximum argument from λ_1 to $\pi\div 2$. The extreme possible boundary limit for U will then be the circle of radius equal to the new effective resistance or

$$\text{Extreme limit for }\underline{U}=|S|\cos\left(\sigma+\frac{\pi}{2}-\lambda_1\right)\text{ cis }\mu$$

$$=|S|\sin(\lambda_1-\sigma)\text{ cis }\mu$$

where μ is any real angle.
Substituting this in the above equation, we obtain as a necessary condition

$$\text{Limit for }U=|S|\cos\lambda_1\text{ cis }(\sigma-\lambda_1)+i|S|\sin(\lambda_1-\sigma)\text{ cis }(\mu-\lambda_1)$$

Since the only variable is the unrestricted real quantity μ this locus for U is the circle of which the center is the first term and the radius the modulus of the second term. The first term is the point at the foot of the perpendicular let fall from the extremity of S on the line cis $(\sigma-\lambda_1)$ and the distance from this point to the extremity of R is $||S|\cos\sigma-|S|\cos\lambda_1\text{ cis }(\sigma-\lambda_1)|$ $=|S||\text{cis}-\lambda_1||\cos\sigma\text{ cis }\lambda_1-\cos\lambda_1\text{ cis }\sigma|=|S\sin(\lambda_1-\sigma)|$, the modulus of the second term.

The corresponding proof for the minimum limit is made by substituting $-\left(\frac{\pi}{2}-\lambda_2\right)$ for $\left(\frac{\pi}{2}-\lambda\right)$. That the lenticular area thus defined is a sufficient as well as necessary restriction is proven by the properties of parallel circuits discussed below.

We may note that U cannot vanish unless there is a range of at least 90 degrees in the impedances of the elements entering the network.

All possible distributions of power between the resistances and the reactances, with any given total driving point impedance may be obtained from two reactive resistances in parallel, and it will now be of interest to examine this case in detail. We will assume that the impedances Z_1, Z_2, when connected in parallel are to have a given total effective impedance S and a given impedance U corresponding to the total power taken by the resistances. These conditions give

$$S=\frac{Z_1 Z_2}{Z_1+Z_2}$$

$$U=\frac{Z_1+Z_1'}{2}\left(\frac{Z_2}{Z_1+Z_2}\right)^2+\frac{Z_2+Z_2'}{2}\left(\frac{Z_1}{Z_1+Z_2}\right)^2$$

$$=\frac{(Z_1 S'-Z_1' S)^2}{2 Z_1^2 (Z_1'-S')}+\frac{S+S'}{2} \tag{27}$$

where the first expression for U is in terms of the resistances and current ratios and the second expression is found by substituting for Z_2 its value in terms of Z_1 and S.

$$\left.\begin{aligned}\text{Let } F&=|F|\operatorname{cis}\varphi=U-\frac{S+S'}{2}\\ S&=|S|\operatorname{cis}\sigma\\ Z&=|Z|\operatorname{cis}\theta\end{aligned}\right\} \tag{28}$$

and put the last expression for U in the form

$$2\,F Z^2 (Z'-S')=(Z S'-Z' S)^2=-4|Z^2 S^2|\sin^2(\theta-\sigma)$$

where subscripts are omitted as the equation applies equally to Z_1 and Z_2. Taking the imaginary part of this equation before and after multiplying by cis $(-\theta-\varphi)$ we have, after dropping the common factors $2|F\,Z^2|i$ and $2|Z^2\,S|\sin(\theta-\sigma)\,i$,

$$|Z|\sin(\theta+\varphi)-|S|\sin(2\,\theta-\sigma+\varphi)=0$$

$$-|F|=2|S|\sin(\theta-\sigma)\sin(\theta+\varphi)=|S|[(\cos(\sigma+\varphi)-\cos(2\theta-\sigma+\varphi)]$$

$$\text{therefore } Z=|S|\,\frac{\sin(2\theta-\sigma+\varphi)}{\sin(\theta+\varphi)}\,\text{cis}\,\theta \qquad (29)$$

with values of θ given by

$$\cos(2\theta-\sigma+\varphi)=\cos(\sigma+\varphi)+|F\div S|$$

which is the required solution for Z_1 and Z_2.

The graphical construction for determining S and U when Z_1 and Z_2 are given, or vice versa, are sufficiently simple to be of assistance. The construction rules which are readily deducible from the preceding work are as follows:

Given Z_1 and Z_2 to find S and U, Fig. 15. Find the impedance S of Z_1 and Z_2 in parallel and draw the circle having S as a diameter, on this circle locate points d_1 and d_2 so that arc $S\,d_1$ = arc $c_1\,R$, and arc $S\,d_2$ = arc $c_2\,R$ where c_1, c_2 and R are the intersections of the circle with Z_1, Z_2, and the resistance axis, using d_1 and d_2 as centers strike circles passing through point R. The other intersection of the circles is the effective impedance U.

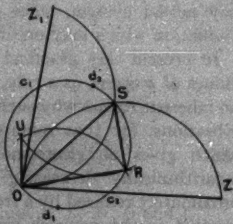

FIG. 15.—Graphical construction for determining the effective driving point impedance (S) and the effective impedance corresponding to the power taken by the resistances (U) for two impedances Z_1 and Z_2 in parallel.

Given S and U to find Z_1 and Z_2. Find the intersections d_1 and d_2 of the circle having S as a diameter and the normal right line bisecting $U\,R$, lay off arc $c_1\,R$ = arc $S\,d_1$, and arc $c_2\,R$ = arc $S\,d_2$. Then $O\,c_1$ and $O\,c_2$ are the direction lines for Z_1, Z_2 the magnitude of which are found by the intersection therewith of the circles tangent to $O\,c_1$ and $O\,c_2$ which have $O\,S$ as a chord.

The vanishing of U requires a difference of 90 degrees in the two impedances Z_1 and Z_2; if the driving point impedance S is to be pure resistance $(=R)$ we have the important case where the parallel impedances are $(R\pm R\,i)$.

Free Oscillations

The characteristic feature of free oscillations is that, throughout the part of the network over which the oscillation extends, the driving point impedance is equal to zero. This follows from the fact that as the driving point impedance is equal to the impressed electromotive force divided by the current, it vanishes when the electromotive force vanishes, provided the current does not vanish. The criterion for free oscillations is therefore

$$A=0 \tag{30}$$

The solution of this equation contains all of the possible values of the time coefficient p. Each possible oscillation is aperiodic or not according as p is pure imaginary or not; p cannot be real for any actual system, since energy must be dissipated in any oscillation which may occur in such a system.

In present day practical applications, complex or imaginary values of p occur, as a rule, only for free vibrations; but there is no inherent reason why such vibrations should not arise as forced vibrations, for that requires only that an alternator be used which gives an electromotive force of constant period and logarithmically decreasing amplitude. This condition is approximately realized by a freely vibrating system which is loosely coupled to the network under consideration.

As an illustration of the application of the method to free oscillations, determine the time coefficients (*i.e.*, the free periods and associated damping constants) for two coupled circuits of impedances Z_1, Z_2, Z_{12}. For this case

$$A=\begin{vmatrix} Z_1 & Z_{12} \\ Z_{12} & Z_2 \end{vmatrix}=Z_1\,Z_2-Z_{12}^2=0$$

$$=[(2\,\delta_1+p\,i)\,(2\,\delta_1'+p\,i)+p_1^2]\,[(2\,\delta_2+p\,i)\,(2\,\delta_2'+p\,i)+p_2^2]$$

$$+k^2\,p^2\,(2\,\delta_1'+p\,i)\,(2\,\delta_2'+p\,i) \tag{31}$$

where $\delta=\dfrac{R}{2\,L}$, $\delta'=\dfrac{G}{2\,C}$, $p=\dfrac{1}{\sqrt{L\,C}}$, $k=\dfrac{M}{\sqrt{L_1\,L_2}}$,

taken with subscripts 1 and 2 to correspond with the circuits. For small damping constants δ, δ' (**31**) may be developed into a series of which the first terms are

$$p\,i = p_0\,i - \frac{\delta_1(p_0^2-p_2^2)+\delta_1'(p_0^2(1-k^2)-p_2^2)+\delta_2(p_0^2-p_1^2)+\delta_2'(p_0^2(1-k^2)-p_1^2)}{2p_0^2\,(1-k^2)-p_1^2-p_2^2}+\dots \tag{32}$$

where
$$p_0 = \sqrt{\frac{p_1^2+p_2^2 \pm \sqrt{(p_1^2-p_2^2)^2+4\,k^2\,p_1^2\,p_2^2}}{2\,(1-k^2)}} \tag{33}$$

are the time coefficients which would obtain if the circuits were free from all dissipative losses.

In the special case of two identical circuits ($Z_1 = Z_2 = Z$) the determinantal equation becomes $A = (Z+Z_{12})\ (Z-Z_{12}) = 0$

$$\text{or } R + (L \pm M)\,p\,i + \frac{1}{G + C\,p\,i} = 0$$

whence
$$i\,p = -\left(\frac{R}{2\,(L\pm M)} + \frac{G}{2\,C}\right) \pm i\sqrt{\frac{1}{(L\pm M)\,C} - \left(\frac{R}{2\,(L\pm M)} - \frac{G}{2\,C}\right)^2} \tag{34}$$

without any restrictions as to the values R, L, M, G and C.

INFINITE NUMBER OF CIRCUITS—EDDY CURRENTS.

When the number of circuits is increased indefinitely the determinant A becomes of infinite order. The particular application which at once suggests itself is that of eddy currents in a cylindrical core. Consider the core of radius a as being made up of a large number n of concentric hollow tubes of thickness $a \div n$ and radii $q\,a \div n$, ($q = 1, 2, \ldots n$) and take as the driving winding another tube of radius $(n+1)\,a \div n$ which has infinite conductivity. Then the impedance for tubes q and r per unit of length is

$$Z_{qr} = Z_{rq} = 2\,\pi\,\rho\left(\delta_{qr}\,q + 2\,z\,i\,\frac{q^2}{n^2}\right), \quad \begin{matrix} 1 \leqq q \leqq r \leqq n+1 \\ \delta_{qr} = \begin{cases} 1 \text{ if } q = r < n+1 \\ 0 \text{ in other cases.} \end{cases} \end{matrix} \tag{35}$$

with $z = \dfrac{\pi\,a^2\,\mu\,p}{\rho} = \dfrac{\mu\,p}{R} = \dfrac{Lp}{4\,\pi\,\rho}$, R and L being the longitudinal resistance ($\rho \div \pi\,a^2$) of the core per unit length and inductance $4\,\mu\,\pi^2\,a^2$ of the driving winding per turn per unit length of core.

The driving point impedance of the winding is, if $x=2zi\div n^2$,

$$S_{n+1}=\frac{A}{A_{n+1,\,n+1}}=2\pi\rho\,\frac{\begin{vmatrix} 1+x & x & x & \ldots & x & x \\ x & 2+2^2x & 2^2x & \ldots & 2^2x & 2^2x \\ x & 2^2x & 3+3^2x & \ldots & 3^2x & 3^2x \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ x & 2^2x & 3^2x & \ldots & n+n^2x & n^2x \\ x & 2^2x & 3^2x & \ldots & n^2x & (n+1)^2x \end{vmatrix}}{\begin{vmatrix} 1+x & x & x & \ldots & x \\ x & 2+2^2x & 2^2x & \ldots & 2^2x \\ x & 2^2x & 3+3^2x & \ldots & 3^2x \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ x & 2^2x & 3^2x & \ldots & n+n^2x \end{vmatrix}},$$

$$=2\pi\rho\,\frac{2\,(n+1)!\displaystyle\sum_{k=1}^{n+1}\left(\frac{zi}{n^2}\right)^k\frac{(n+k)!}{(k-1)!\,k!\,(n+1-k)!}}{n!\displaystyle\sum_{k=0}^{n}\left(\frac{zi}{n^2}\right)^k\frac{(n+k)!}{(k!)^2\,(n-k)!}}$$

the transformation of the determinants into series of powers of $x\div 2=zi\div n^2$ is proven to be correct by its being true for $n=1$ and 2 and satisfying the difference equations for the numerator (N_n) and the consecutive values of the denominator (D_{n-2}, D_{n-1}, D_n and D_{n+1})

$$N_n=D_{n+1}-(n+1)\,D_n$$

$$D_n=(2n-1)\,(1+x)D_{n-1}-(n-1)^2D_{n-2}$$

which are obtained by adding $(n+1)\,D_n$ to N_n, that is increasing its last element by $(n+1)$, which becomes D_{n+1} and by expanding D_n according to the last row and column after subtracting therefrom the next to the last row and column. For $n =$ infinite,

$$\left.\begin{aligned} S &= 2\pi\rho \frac{2\sum_{k=1}^{\infty}\frac{(z\,i)^k}{(k-1)\,!\,k!}}{\sum_{k=0}^{\infty}\frac{(z\,i)^k}{(k!)^2}} \\ &= 2\pi\rho \frac{2\,z\,i+(z\,i)^2+\frac{(z\,i)^3}{6}+\;.\;.\;.}{1+z\,i+\frac{(z\,i)^2}{4}+\frac{(z\,i)^3}{36}+\;.\;.\;.} \\ &= 2\pi\rho \frac{-\sqrt{-4\,i\,z}\,J_1\sqrt{-4\,i\,z}}{J_0\sqrt{-4\,i\,z}} \\ &= 4\pi\rho z\,\frac{d}{d\,z}\log J_0\sqrt{-4\,i\,z} \\ &= 4\pi\rho z\,i\left(1+\frac{J_2\sqrt{-4\,i\,z}}{J_0\sqrt{-4\,i\,z}}\right) \end{aligned}\right\} \qquad (36)$$

which are the well known results expressed in Bessel's functions, To make the formula perfectly general for any driving winding it is necessary only to multiply by the length of the core and the square of the total number of turns in the winding and to add the impedance of the winding which arises externally to the core.

This example shows that certain infinite systems of circuits which are ordinarily solved by partial differential equations may be handled by the general determinantal solution, but of course when transcendental functions are involved, as in the case of eddy currents, the algebraical reduction may introduce some complexity.

Eddy currents in transformer plates give the following results:

For a plate of thickness $2a$, width w and axial length l divided into a large number of $2n$ of sheets of equal thickness and surrounded by a close fitting driving winding of a single turn and zero resistance:

$Z_{qr} = Z_{rq} = \frac{2\,\rho\,w\,n}{a\,l}\left(\delta_{qr} + 4\,z\,i\,\frac{q}{n^2}\right)$, $z = \frac{\pi\,a^2\,\mu\,p}{\rho}$, q, r and δ_{qr} as above and the driving point impedance at limit n = infinite is

$$S = \frac{2\,\rho\,w}{a\,l}\sqrt{4\,z\,i}\tanh\sqrt{4\,z\,i} \tag{37}$$

Skin Effect

For a cylindrical conductor of radius a, length l and steady current resistance R with close fitting return shell of zero resistance, the conductor being divided into n concentric tubes of equal cross section with circuit q comprising adjacent tubes q and $q+1$:

$$Z_{qr} = Z_{rq} = \frac{\mu\,l\,p\,n}{z}\left(\delta_{qr} + \frac{z\,i}{n\,q}\delta'_{qr}\right) \qquad \delta_{qr} = \begin{cases} 2, \text{ if } q=r<n \\ 1, \text{ if } q=r=n \\ -1, \text{ if } q=r\pm 1 \\ 0, \text{ in other cases} \end{cases}$$

$$\text{with } z = \frac{\pi\,a^2\,\mu\,p}{\rho} = \frac{\mu\,p\,l}{R} \qquad \delta'_{qr} = \begin{cases} 1, \text{ if } q=r<n \\ 1\div 2, \text{ if } q=r=n \\ 0, \text{ in other cases} \end{cases}$$

and the driving point impedance at limit n = infinite is

$$S = -\frac{2\,\mu\,l\,p\,i}{\sqrt{-4\,i\,z}}\,\frac{J_0\sqrt{-4\,i\,z}}{J_1\sqrt{-4\,i\,z}} \tag{38}$$

Details of Proof. Regard each hollow cylindrical tube as concentrated on its mean diameter, while retaining its actual resistance, $\rho\,n\,l \div \pi\,a^2$. This resistance with sign changed will then be the mutual impedance between any two adjacent circuits, as each tube carries the difference between the currents in the two adjacent circuits of which it forms a common part; no other mutual impedances occur, as no other current products enter the expression for the total energy. The self-impedance of the qth circuit is made up of twice this resistance, together with the inductance $l \div q$; the inductance being found by the single turn solenoid formula 4π cross-section ÷ length, the cross section being $a\,l \div 2\sqrt{q\,n}$ and the length (*i.e.*, mean circumference) being $2\,\pi\,a\sqrt{q \div n}$. For the outermost circuit ($q = n$) this impedance is to be divided by two, since its return circuit is of zero resistance and zero thickness. The impedances Z_{qr} are thus, as stated above. After removing the factor $\mu\,p\,l\,n \div z$ from each element of determinants A and A_{nn} and placing $x = zi \div n$, we have

$$S = \frac{A}{A_{nn}} = \lim_{n=\infty} \frac{\mu p l n}{z} \frac{\begin{vmatrix} 2+\frac{x}{1} & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2+\frac{x}{2} & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2+\frac{x}{3} & \cdots & 0 & 0 \\ \cdot & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdot & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 2+\frac{x}{n-1} & -1 \\ 0 & 0 & 0 & \cdots & -1 & 1+\frac{x}{2n} \end{vmatrix}}{\begin{vmatrix} 2+\frac{x}{1} & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2+\frac{x}{2} & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2+\frac{x}{3} & \cdots & 0 & 0 \\ \cdot & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdot & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 2+\frac{x}{n-2} & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2+\frac{x}{n-1} \end{vmatrix}}$$

$$= \frac{\mu p l}{z} \frac{\lim\limits_{x=\infty} \sum\limits_{k=0}^{n} \frac{(2n-k)\ (n-1)!}{2\,(k!)^2\,(n-k)!} x^k}{\lim\limits_{x=\infty} \frac{1}{n} \sum\limits_{k=0}^{n-1} \frac{n!}{k!\,(k+1)!\ \ (n-k-1)!} x^k}$$

the correctness of the series expansions for the determinants is readily proven for $n=1$ and 2 directly from the determinants and then extended step by step to any value of n by expanding the determinants according to the terms in the last row and column so as to obtain expressions for the denominator (D_n) and the numerator (N_n) in terms of the denominator with different values of n, *viz*:

$$D_n = \left(2+\frac{x}{n-1}\right) D_{n-1} - D_{n-2}$$

$$N_n = \left(1+\frac{x}{2\,n}\right) D_n - D_{n-1} = D_{n+1} - \left(1+\frac{x}{2\,n}\right) D_n = \tfrac{1}{2}\,(D_{n+1} - D_{n-1})$$

which are readily shown, by substituting the above series expressions, to be identically satisfied for all values of n.

Finally replacing x by its value $z\,i \div n$ and passing to the limit, $n=\infty$

$$S = \frac{\mu p l}{z} \; \frac{\displaystyle\sum_{k=0}^{\infty} \frac{(z\,i)^k}{(k!)^2}}{\displaystyle\sum_{k=0}^{\infty} \frac{(z\,i)^k}{k!\,(k+1)!}}$$

which is identically formula (**38**), as the numerator is the series for $J_0\sqrt{-4\,i\,z}$ and the denominator is the series for $2\,J_1\sqrt{-4\,i\,z} \div \sqrt{-4\,i\,z}$.

SUMMARY

1. The complex exponential function is shown to be, not a symbolic vector representation of the sinusoidal function, but a scalar function of fundamental importance in its own right, and enjoying algebraical power and energy relations as important as those of real functions. In order to emphasize the basic and distinctive character of the complex exponential function, it is given the name "cisoidal oscillation."

2. The correlation between sinusoidal oscillations and cisoidal oscillations is reduced to a few simple rules which cover power as well as currents and electromotive forces.

3. The general law of distribution of currents in any invariable network is shown to be that of stationary dissipation of power.

4. The law of distribution of cisoidal currents in any invariable network is reduced to that of stationary total power, or to the equivalent condition of stationary driving point impedance or admittance.

5. The cisoidal power is employed as the most convenient means for investigating the division of the instantaneous power between the resistances and reactances of a network.

6. The general solution for cisoidal oscillations in any invariable network is given in determinantal form and it is shown how the various impedances of any particular network may be written down at once and how the elimination of concealed circuits, mutual impedances or self-impedances may be accomplished. Applications to impedance loci, free oscillations and infinite systems of circuits are also given.

DISCUSSION ON "CISOIDAL OSCILLATIONS," LOS ANGELES, APRIL 25, 1911.

C. L. Cory: In order to obtain a physical and in fact practical conception of the results obtained by Mr. Campbell as treated mathematically in his paper, it may be well to consider one of the comparatively simple conditions existing in a circuit containing resistance R and inductance L, there being applied to this circuit an electromotive force having an instantaneous value e, which varies with time t.

In such a circuit the equation which expresses the value of the instantaneous electromotive force, interpreting the equation physically rather than expressing it mathematically, is that the instantaneous electromotive force e applied to such a circuit is expended in two ways; first, to overcome the resistance of the circuit or $R\,i$; and second, to overcome the electromotive force of self-induction in the circuit or $L\,\frac{d\,i}{d\,t}$.

Mathematically such an equation would be as follows:—

$$e=R\,i+L\,\frac{d\,i}{d\,t}.$$

Even with such a comparatively simple equation it can not be solved to give us practical results unless we know or assume the law by which the electromotive force varies with time. However, practically we assume a sine function of the time, and we therefore have: $e=E\sin w\,t$, in which E is the maximum value of the electromotive force and w is equal to $\frac{2\pi}{T}$, where T is the time of a complete period.

Instead of having circuits containing resistance R and self-induction or inductance L, only, as we well know, we may have a circuit which contains resistance and electrostatic capacity, or a more complex circuit which contains resistance, inductance and capacity, or a still more complex condition of the circuit or network which contains resistance, inductance, capacity and mutual inductance.

The mutual induction in a circuit can, however, very readily be represented by an equivalent self-induction.

If a variable electromotive force is applied to any of the above circuits and we assume that such electromotive force varies as a sine function of the time, and we solve for the practical values or virtual or effective current and electromotive force, as well as equivalent resistances, reactances and impedances, we get what mathematically is known as the constant of integration. It is this constant of integration which Mr. Campbell has so beautifully and completely treated in his paper. Let us discuss from a strictly physical standpoint this constant of integration.

In an ordinary alternating current circuit we know that if we could succeed in opening or closing such a circuit at the instant when the current is passing through its zero value practically we would get no arc or, except for causing a cessation or establishing the current, we would not introduce electrical disturbances in the circuit. It is of course practically impossible to make and break circuits at exactly the instant when the current value is zero, and as a result if we close or open a switch in an alternating current circuit containing resistance, self-induction, capacity or mutual induction, which may be made the equivalent in self-induction, we produce disturbances or oscillations in such a circuit over which we have practically no control as compared with the fundamental sine wave of current and electromotive force.

For the most part we have neglected this constant of integration because we have assumed that the disturbance or oscillations introduced in such a circuit very soon disappear. This, however, is not the fact where self-induction and capacity both are contained within such a circuit.

Even with self-induction and resistance only, or capacity and resistance only, theoretically the resultant current from such oscillations will never become zero. Practically, however, the resultant current in such circuits very soon becomes zero.

Referring to Mr. Campbell's paper, equation No. 1, and the last term of that equation, which is $C\,e^{ipt}$, it may be said that this term is of the nature of the constant of integration to which reference has been made above, but in order that we may adopt symbols to correspond with those used in the paper it should be remembered that C and p are constants either real or complex and that e is the Naperian base and i is the imaginary symbol corresponding to j as used by Steinmetz.

The term p is a constant, either real or complex, and represents the condition of the circuit or network as regards self-induction, capacity and mutual induction, and the other letters of the equation represent quantities as above explained.

Let us now turn to a few paragraphs of Mr. Campbell's paper in order to ascertain in a general way his method of treatment of the subject, the mathematical character of "cisoidal oscillations" and his extremely valuable and specific results and conclusions regarding such oscillations in circuits of the character of existing telephone distribution systems.

In the first place, the paper is not only mathematical but it is more than that; it is metaphysical in its treatment. The author has clearly pointed the way to the treatment of these peculiar oscillations and indicated a method whereby we may thoroughly understand the action, although we may not have control over the establishment, of such oscillations.

In a way his treatment of the subject is analogous to the mathematical treatment of alternating currents many years ago, in which it was shown that the laws of direct currents would not hold for the newly developed alternating currents. In this paper we have the mathematical treatment of these peculiar oscillations, which is a distinct addition to the mathematical treatment of alternating currents in somewhat the same manner as the mathematical treatment of alternating currents was a distinct step in advance of the equations which were satisfactory for direct currents.

To understand the character of these oscillations we need only consider a portion of the first paragraph of the paper, in which it is stated that these oscillations are sustained logarithmically, damped, or aperiodic, depending upon whether the time coefficient p, which really indicates the character of the circuit, is real, complex or purely imaginary. Further, the author has used the term "cisoidal oscillations" in order to emphasize the distinctive character of such oscillations and at the same time to indicate the close relation between such oscillations and the more generally known sinusoidal oscillations.

It is apparent, especially in telephone circuits, that while primarily we have to deal with oscillations which may be assumed equivalent to sinusoidal oscillations, yet in such circuits containing resistance, inductance and capacity it is quite as necessary to understand the laws governing this new kind of oscillation to which the author has given the name "cisoid."

We may get a somewhat clearer idea of these oscillations, as the author states that they are uniquely simple, because the ratio of the instantaneous electromotive force to the instantaneous current is not a function of the time.

Further we are told that the solution for cisoidal oscillations in any finite network may be written down directly without solving differential equations or the use of integration or differentiation.

The author brings out the fact that the use of vectors in the solution of complex quantities in alternating current theory is unfortunate and logically incorrect, and that the tendency of such use of vector quantities in ordinary alternating current theory tends to divert attention from the algebraic theory of complex quantities, which are of the greatest practical assistance in the mathematical treatment of cisoidal oscillations.

The mathematical treatment of the subject by Mr. Campbell in general is to use the mathematical process known as determinants, in order to obtain what he calls the discriminant A of a network, and in Table I, is to be found effective impedances or equivalent networks with two accessible circuits in terms of each other, and of the determinant A. As showing that these peculiar oscillations may be indefinitely sustained and that therefore they must be given consideration in telephone circuits, we find a statement to the effect that the activity of the external sources of power which produce *steady* cisoidal oscillations in any invariable network or one the constants of which remain invariable may assume a stationary value providing such value is consistent with the conditions necessary for current continuity and the conservation of energy.

The author has indicated in a most satisfactory manner the mathematical treatment for the conditions existing in an infinite number of circuits which correspond to our well-known eddy currents and to the skin effect, or the unequal distribution of current throughout a cylindrical conductor, which as we know involves conditions regarding which we must make allowances for certain quantities of current for frequencies above those nominally used.

In conclusion, and referring to the summary given in the paper, the author interprets his results from the mathematical standpoint, which concisely are:

1. The complex exponential function or mathematical expression of cisoidal oscillations is a mathematical term of fundamental importance in its own right and enjoys algebraic power or energy relations quite as important as those of real functions.
2. The correlation between sinusoidal and cisoidal oscillations may be reduced to a few simple rules covering power, currents and electromotive force.
3. The distribution of currents in any network of conductors having constant values is that of stationary dissipation of power.
4. The distribution of cisoidal currents in such a network is reduced to the equivalent condition of stationary driving point impedance or admittance.
5. The cisoidal power may be and is employed as a most convenient means for investigating the division of instantaneous power between resistances and reactances of a circuit or network.
6. Determinants may be used for the general solution of cisoidal oscillations in any invariable network or network having constant values, and the author has shown how the different impedances of such a network may be found directly and has also indicated how concealed circuits, mutual impedances or self-impedances may be eliminated. Also the author has given applications covering free oscillations and infinite systems of circuits.

In conclusion it should be said that not only is this paper of Mr. Campbell's fascinating from the standpoint of the application of mathematics to physical problems, but he has indicated a method of accurately determining the conditions existing in telephone circuits in which there are oscillations due to self-induction and capacity over which in practice we have practically no control, and if you can imagine conditions in a circuit in which the ratio of instantaneous electromotive force to instantaneous current is not a function of time we can to a small degree appreciate into what depths Mr. Campbell has extended his investigations leading to the solution of what are unquestionably some of the most important problems to be met in the transmission of telephonic currents in extensive telephone transmission systems.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, April 26, 1911.

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NEW AUTOMATIC TELEPHONE EQUIPMENT

BY CHARLES S. WINSTON

Automatic schemes for establishing connections between telephones were devised early in the history of the telephone movement and many of the first patents, which were issued for telephone inventions, were for devices which are the forefathers of the automatic equipment in use to-day.

During the first 25 years of telephony's history, a few automatic switchboards were installed, but it was not until the installation of the exchange at Grand Rapids, in 1903 that automatic apparatus received very serious consideration from the general public or from engineers, with the exception of a few who were, in most cases, personally interested in its advancement. During the last eight years interest in the automatic method has increased, many articles in regard to it have been written, and now a casual mention of the subject in almost any gathering of men in the telephone business is enough to cause heated discussion in regard to the relative advantages of manual and automatic. Recently new foes, near relatives, of automatic have appeared upon the horizon, which seem destined to play very important parts in the history of the telephony of the future—the automatic-distributing and semi-automatic systems.

In order to prevent misunderstanding, it may be well to state that throughout this paper a switchboard which requires automatic calling devices or dials at the subscribers' stations and no operators at the central office will be referred to as an automatic switchboard. An automatic-distributing switchboard will be one in which automatic switches are used for distributing calls to idle positions where operators establish connections by means of plugs and multiple jacks, as in the well known manual multiple switchboard, and a switchboard in which the connections between lines are made by means of automatic switches, which are operated by devices manipulated by operators, will be referred to as a semi-automatic switchboard.

The work of designing, perfecting and manufacturing an entirely new line of automatic equipment requires an immense amount of study and experiment. For sometime the company with which the writer is associated has been developing apparatus which will enable it to manufacture automatic equipment which will meet all of the requirements of automatic, automatic-distributing and semi-automatic. In this article a description will be given of parts of this apparatus which it is not expected to use in practice, but which may be of interest from an historical standpoint, as well as of apparatus which with certain changes will, in all probability, be put to practical use in the near future.

Different types of switches are not required for each of these branches of automatic, as the switches which are suited for one can, with slight modifications, be used equally well for the others.

Up to the present time, the "Strowger" switch is the only one which has been used to any extent. When used as a selector, the wipers of this switch, which are attached to the shaft, move vertically in response to current impulses caused by the operation of the subscriber's dial, and then rotate horizontally until idle trunk contacts are reached. The switches of the five following types will do the same work as that done by this switch, but in a radically different manner. For the lack of more satisfactory names, the switches will be referred to as:

1. Circular polywiper.
2. Circular long and short step with one driving magnet.
3. Circular long and short step with two driving magnets.
4. Double rotary with back release.
5. Double rotary with forward release.

1. CIRCULAR POLYWIPER SWITCH

Fig. 1 shows a plan view of the circular polywiper switch and a side elevation with certain parts in section. For all practical purposes it consists of two separate switches, each with a distinct driving magnet, wipers and bank contacts, which are built together in one structure to economize space and to facilitate wiring.

Instead of following the usual practice of attaching flexible cords to the wipers and thus continuing the circuit to the desired contacts of the bank, wires are carried to circular metal strips immediately below but insulated from the rows of individual contacts. The wipers serve to bridge together the individual contacts and these circular strips. In this manner all cord troubles are eliminated, although there are two movable contacts in each connection instead of one.

The bank consists of five circular rows of contacts, each row being divided into ten equal groups. There are two sets of wipers—the primary *P* and the secondary *S*. The former consists of ten separate single wipers which are mounted upon 36-deg. centers on the plate 1, which is rigidly secured to the shaft *P S*, while the secondary wipers consist of 10 sets of four wipers each, mounted similarly upon plate 2, which in turn is fastened to the shaft *S S*. The two shafts *P S* and *S S* are attached to ratchet wheels *P R* and *S R* respectively and through them the primary wipers are controlled by the magnet *P M* while magnet *S M* controls the secondary wipers.

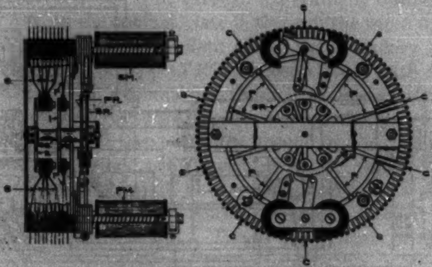

FIG. 1.—Circular polywiper switch

When in normal position, the primary wipers *P* rest upon contacts *C* and the secondary wipers *S* upon the contacts in line with and below contacts *C*, while these connections will be broken when the wipers are moved forward by the operation of the driving magnets. When the wipers have moved 11 steps the same condition will again be met and the switch will again be in normal position.

In Fig. 2 is shown the wiring of a first selector, individual to a line, using a switch of this type, with the wiring of a subscriber's telephone including a calling device. When the switch is normal the 10 primary wipers will be in the positions shown at *P*, while *S* represent the positions of the various secondary wipers. The common strips *M*, *N*, *O*, *M*1, *M*2, *M*3, etc., are each associated with 10 contacts instead of three as shown. The system illustrated uses a single source of current for both signalling and talking, while a ground return circuit is used for operating the relays which in turn operate the magnets which move the switch wipers.

In order to assist in giving an understanding of this switch, the method of operation of the circuit shown will be described briefly.

A subscriber desiring to converse with a second subscriber will remove his receiver from its hook, thus establishing a path for current through relays *P R* and *S R* and the apparatus in his instrument. He will then operate the calling device, thus connecting springs *A* and *B* to ground and breaking contact *c* a definite number of times, while current flowing from ground over line conductor *L*2 will maintain relay *S R* in the energized position. Each time the circuit is broken in this manner, relay *P R* will be de-energized and contact *E* closed, thus sending current through the primary magnet *P M*, and causing the primary wipers of the switch to make a certain number of steps. (Secondary contacts *K*1 and *K*2, *K*3 and *K*4, *K*5 and *K*6, *K*7

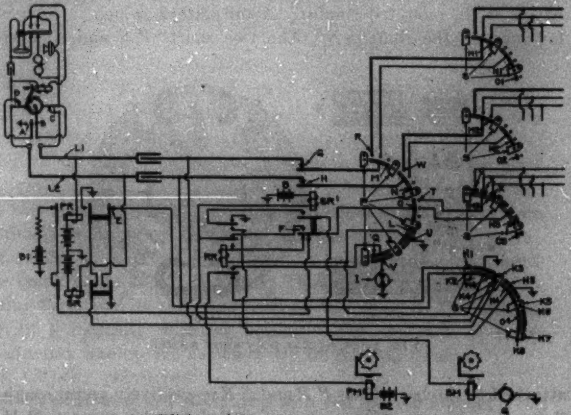

FIG. 2.—Wiring of first selector polywiper switch

and *K*8 are connected together through wipers whenever the switch is in the normal position.) Immediately thereafter and just before the calling dial returns to normal, both line wires remaining grounded, contact *D* will be broken once, thus holding relay *P R* energized and causing one de-energization of relay *S R*. For the purpose of illustration, suppose that the subscriber desires conversation with a second subscriber whose number begins with one. The primary magnet would then take one step, establishing connections between *M*, *N*, *O*, *L* and *Q*, and *R*, *W*, *T*, *U* and *V* respectively. Immediately thereafter, the de-energization of relay *S R* as above explained, will cause the energization of relay *S R′*. It will be noticed that the energization of the latter relay will establish a circuit from the negative pole of battery *B*, through the winding of this relay, back contact of relay *R R*, through the normally open contact *F* of relay *S R′* to the contact plate 0, through the wiper to contact *T*, and thence to common plate *M*3 of the secondary contacts. The energization of relay *S R′* will also close a path from the alternating-current generator *G* through the secondary magnet *S M*, thus moving forward the secondary set of wipers *S*. If the private contact *x* is busy, due to a ground on the corresponding contact of some other switch, relay *S R′* will remain energized and the switch wipers will be stepped ahead until a contact is found which is clear, when relay *S R′* will be de-energized and the switch will come to rest. The de-energization of relay *S R′* will close the talking circuit from the subscriber's instrument, through contacts *G* and *H*, and the primary wipers and concontacts, to the secondary wipers and thence to a second selector.

When the subscriber returns his receiver to its hook, relays *P R* and *S R* will be de-energized, thus causing relay *R R* to be energized by current flowing from ground at switch contact *U* to the negative pole of battery *B*1 and locking relay *R R* through *S R′* to battery *B*, thus cutting off the circuit from battery *B*1. The energization of the latter relay will again establish a circuit through the secondary magnet *S M* to ground at *N*5, while the energization of relay *R R* will cause current to flow from battery *B*2 through the winding of the primary magnet *P M*, a primary wiper and contact *V* to ground, through the interrupter *I*. The energization of these two magnets will be continued till the wipers have been driven ahead until they rest at *P* and *S* upon the normal contacts between the groups, at which time the circuits for all relays will be opened and all apparatus will be in normal position.

In the circuit shown, but five of the ten primary groups of contacts are used. It will, therefore, be seen that a large number of contacts are available for use as "off normal" contacts if the circuit requirements make it desirable. This feature of the switch is one of its chief advantages, but the difficulties which are necessarily met with in assembling and in wiring make it impracticable from the standpoint of manufacture and operation.

2. CIRCULAR LONG AND SHORT STEP SWITCH WITH ONE DRIVING MAGNET

As shown in Fig. 3, the construction of the long and short step single driving magnet switch is similar in general appearance to the polywiper switch, there being 10 circular groups of 10 contacts each. However, there is but a single set of wipers, which when moved forward by the driving magnet *M*, the magnet *M'* being de-energized, passes over one group of ten contacts at each step. If, however, magnet *M'* is energized at the time when the wipers are being stepped forward, the movement of armature *A* will be shortened by the stop *S* and the wipers will move from one set of contacts to the adjacent contacts for each energization of magnet *M*. As will be seen from this statement, each one of the 10 circular sets of contacts corresponds to a row of contacts on a vertical and rotary switch. That is, in this switch the wipers instead of moving a certain number of steps in one direction and then rotating at right angles, move a certain number of long steps and then take short steps

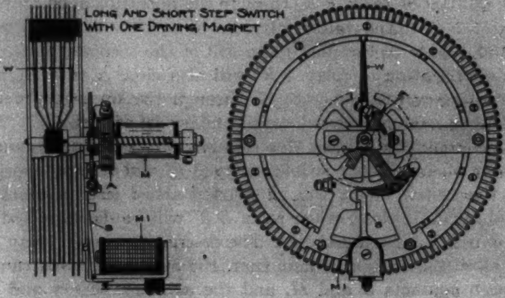

FIG. 3.—Long and short step switch with one driving magnet

until they arrive at contacts of a trunk line which is not in use, in the case of a selector, or until the contacts of the desired line are reached, in the case of a connector.

3. CIRCULAR LONG AND SHORT STEP SWITCH WITH TWO DRIVING MAGNETS

This switch is very similar to the one just described. The only difference of importance is that instead of using a magnet to limit the stroke and hence to move the wipers from one contact to the next, two separate magnets are employed, one for giving the long steps and one for giving the short.

4. DOUBLE ROTARY SWITCH WITH BACK RELEASE

It will be seen upon referring to Fig. 4, which shows this switch as a first selector, that the contacts are mounted in 10 separate strips or groups, each of which has 10 sets of contacts (each set consisting of two line contacts and one private contact) arranged in an arc of a circle, so that when completely assembled, all contacts point inwardly toward a common center,

Instead of using a single shaft, with the wipers rigidly attached. which moves vertically to select a group of contacts and then revolves horizontally to select the trunk, two shafts are used in this switch. One, to which the wiper frame is directly connected, rotates in a horizontal plane to select the group. The second is so connected to this frame that its downward movement gives the wipers a second rotary movement, thus stepping them upward into engagement with the bank contacts. Primary and secondary magnets are used for accomplishing these results, and the switch is returned to normal by means of a release magnet. Because of the relative arrangement of shafts and wipers, the latter move four or five times as great a distance as the former for each energization of either the primary or secondary driving magnet, and hence the movement of the armatures of these magnets is exceedingly small. It has been found from experiment that, due to this construction, switches of this type operate satisfactorily when the voltage of the storage battery used therewith is as low as 35 and that the height to which the voltage may rise does not affect the operation, as current of any voltage which the relays, used with the switch, can stand without injury may be employed. Hence, it is not necessary to use two sets of batteries—one for discharge while the other is being charged—or to resort to the use of extra storage cells or counter e.m.f. cells to maintain a constant voltage.

This switch is constructed so that the switch proper, consisting of relays, wipers and driving magnets, is supported by the frame of the contact bank in such a way that the switch can be removed instantly if trouble occurs without it being necessary to unsolder wires. The contact bank is fastened to the iron framework which supports all switches and hence the multiple wires do not support the bank when a switch is removed.

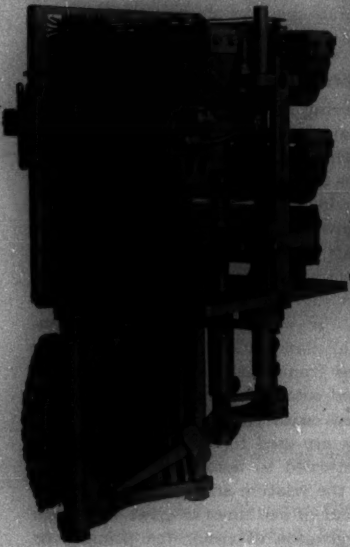

Fig. 4

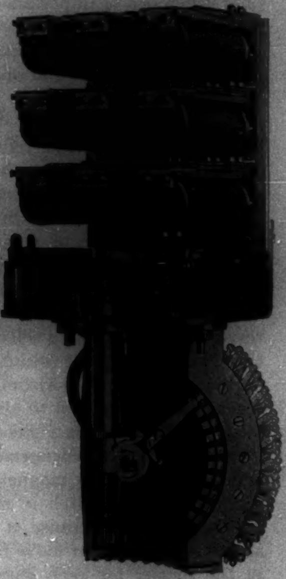

Fig. 5

5. Double Rotary Switch with Forward Release

This switch, which is shown in Fig. 5 as a connector, is similar in many respects to the switch just described. The arrangement of the bank contacts is similar although more space is provided in this switch in order to facilitate the multiple wiring. Primary and secondary magnets give the wipers a double rotary motion but, in releasing, the magnet which has caused the vertical movement is again brought into use and the wipers are driven forward to the end of their vertical stroke. When this position is reached, a projection carried upon the wiper arm releases a retaining pawl, which has kept the wipers in the position into which they were driven by the primary magnet, thus allowing the wipers to move horizontally due to spring tension. When they have returned in this direction as far as possible, which is to a position directly above their normal position, a second retaining pawl, which after each vertical step has kept the shaft in its vertical position, will be released and the wipers will be returned to normal position.

As the release of this switch is accomplished by driving the wipers forward, clean contacts are at all times assured. In back release selector switches the last contacts in all rows are used infrequently, and hence they become coated with dirt and grease, thus preventing satisfactory connections when it becomes necessary to use them. Another advantage of this type of construction is that the wear on all contacts will be equal and hence the life of the bank increased.

During the last year a life test was made with a switch of this type. The switch was subjected to all the mechanical and circuit changes which it would undergo in practice in operating 1,378,000 times, which is equivalent to the use which an average switch in an exchange of 10,000 lines, would receive in 37 years' service. As, however, the wipers continuously passed over the tenth row of contacts, instead of each of the ten an equal number of times, the wear on these contacts was equal to what it would be in 370 years of service.

AUTOMATIC CALLING DEVICES

Second only in importance to the selector and connector switches, if it is not of equal or even greater importance, is the calling device used at the subscriber's station. The design of a calling device which will meet all conditions of service is an extremely difficult problem. The work to be done requires complicated mechanism which, as it is to be used by unskilled hands, must be strong, positive in operation and "fool-proof." If a switch fails to properly perform its functions an attendant who is always present can remedy the trouble, but trouble in a calling device makes necessary a trip of the troubleman at an expense which may not be small.

It is possible to design calling devices of a great many different types, and numerous patents have been issued for schemes of various kinds. In connection with the automatic development referred to, calling devices of six or seven different types have been made. Some are of the "finger-hole" type, others employ a lever for their operation, while one has been developed in which the subscriber sets up the number of the desired station on the face of the device before sending the impulse. A cut of this device is shown in Fig. 6. Upon referring to this figure it will be seen that there are in the top plate five circular openings through which digits are visible. Extending from the side of the device below these openings are five buttons which when turned either to the right or to the left change the figures from 1 to 0. Therefore, it is possible to set up any number between 00000 and 99999, or in other words to use this device as shown, in a one-hundred thousand line system.

The method of procedure in making a call with this device is as follows: The subscriber removes the receiver from its hook, turns the buttons in the calling device (this can also be done before removing the receiver if desired) until the proper number appears, and turns the lever at the right hand end until a stop is reached. The mechanism within the device will then operate and cause the operation in succession of the selector and connector switches. During the time that the impulses are being sent, the figure-changing buttons, as well as the sending lever, will be locked so that the subscriber cannot interfere with the signalling.

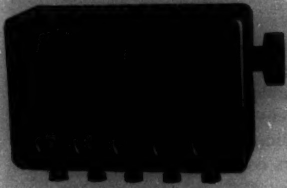

Fig. 6

The advantages of an instrument of this type are obvious. With calling devices of the usual type, a very large percentage of the errors made in calling are due to mistakes of the subscribers, and not to the apparatus, but such errors cause complaint and dissatisfaction and often the loss of subscribers. A calling device of this type will eliminate such errors entirely. The objection has been made to any device in which the number is set up, that if a wrong station is called and the subscriber sees that the proper number is before him, he will know that the fault is in the equipment, and the eloquence of the troubleman cannot change his view. This is seemingly very weak argument as automatic apparatus which must rely upon such subterfuges to retain the good will of the users is not what it should be.

One of the calling devices, of the finger-hole type, which has been developed possesses several novel features. In operating, the finger is placed in the hole associated with the proper number and the front plate rotated until a stop is reached. When the finger is withdrawn the front plate rotates backward, under the control of a very simple governor, breaking a contact a definite number of times. The mechanism is not locked at any time and the subscriber must use care to complete the movement of the dial and not to retard the front plate during its backward stroke. If either of these precautions is disregarded the call will not be made properly. This dial is very simple and inexpensive and the cost of maintenance would unquestionably be very low. It is, however, extremely doubtful whether, in the present state of automatic, the general public can be relied upon to use the precautions necessary for the satisfactory operation of so simple a dial, but if automatic exchanges increase in number it will not be surprising to see a simple dial of this sort used, as soon as telephone users are sufficiently educated.

CONNECTING CALLING LINE TO SWITCHES

Various methods have been employed in automatic systems for connecting the subscribers' lines to the first selectors. The old Strowger plan, which is used in a large number of automatic installations, provides an individual first selector for each line, and it is very doubtful whether any of the other schemes which have been used up to this time are its equal when the cost of maintenance is considered as well as initial cost. Several years ago engineers saw that an individual first selector was more expensive than necessary and various substitutes have been devised. The scheme which up to this time has been most extensively used, is the so-called "Keith Unit" which has been described so frequently that description here would be superfluous.

Another scheme which has been proposed is the "back-selecting" scheme. Two relays, a line and a cut-off, are furnished for each line, and when a call is initiated, the energization of the line relay sets in motion the wipers of a line-finding switch, which travel over bank contacts until they come to contacts which are attached to the calling line, where they stop and thus connect the calling instrument to a first selector.

Another plan which has not yet been used in practice but which has many advantages is to use a small 10- or 15-point line switch for each line. In addition to the switch mechanism, which includes one driving magnet, two or possibly three relays per line are required in order to bring about the necessary circuit changes. With this scheme, when a subscriber removes his telephone from the hook, a line relay will be energized and current will be sent through the driving magnet, which will step forward the switch wipers. When contacts which are attached to an idle first selector are reached, the movement of the wipers will cease and the circuit will be continued from the subscriber's instrument to the selector. As one switch is required for each line, it is possible that, although it is comparatively inexpensive, the cost will be greater than that of either of the two other schemes mentioned, but a slight additional cost is seemingly justifiable in order to make it impossible for trouble in a switch to throw out of service more than one line. With the individual line switch, trouble in the line switch may prevent the associated line from calling, but it can have no effect upon a second line. The circuit of a switch of this type will be shown later in connection with the description of the circuits of a complete two-wire system.

AUTOMATIC SWITCHBOARD

The automatic switchboards installed previous to the last few years used local battery in each instrument for furnishing talking current while the signalling was accomplished by means of current from a storage battery located at the central office. These systems were "three-wire" systems in which the signalling current returned from the subscriber's station through the earth. As electric car lines and electric lighting plants increased in number, it was found that, as in other branches of telephony, earth potentials caused trouble, thus making it necessary, in extreme cases, to substitute for the earth return an additional wire for each line or a common return wire, which served a number of lines.

The first common battery automatic installations were also three-wire systems, but the trouble due to signalling through ground was so great that it was necessary for engineers to devise means which would enable the signalling to be done over a metallic circuit. A number of plans were proposed, one of which was the use of the "slow-acting" relay. That is, a relay which, when energized by current, will hold its contacts closed for a short period after the circuit through its winding has been broken. The means generally used for accomplishing this result is either to place a copper sleeve over the core of the relay or a large amount of copper over one end of the core. A relay built in either of these two ways answers the purpose admirably and by increasing or decreasing the air space between the armature and the pole piece, varying degrees of sluggishness can be obtained.

The circuits of a two-wire system including a subscriber's instrument with a calling device of the "set-up" type, an individual 10-point line switch, first selector, second selector and connector, using the double rotary switch with forward release, are shown in Figs. 7 to 10. It should be borne in mind that it is improbable for various reasons that the circuits shown or the apparatus will be used in practice without changes of a more or less radical nature.

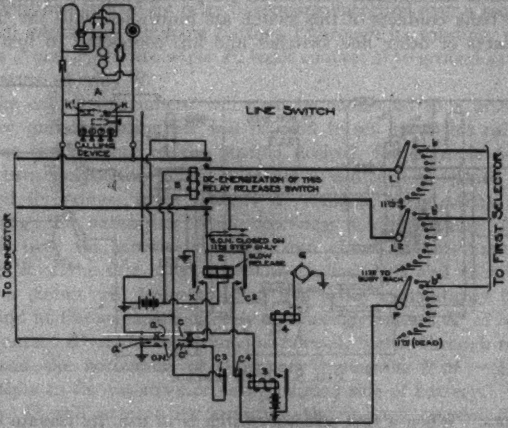
A
K'
K
CALLING DEVICE
LINE SWITCH
5
DE-ENERGIZATION OF THIS RELAY RELEASES SWITCH
L'
L²
S.O.N. CLOSED ON 11TH STEP ONLY
2
SLOW RELEASE
X'
C2
6
11TH TO BUSY BACK
1
4
a
a'
c
c'
O.N.
C3
C4
3
11TH (DEAD)
TO CONNECTOR
TO FIRST SELECTOR

FIG. 7.—Line switch

The various steps which take place in establishing a connection between two stations as *A* in Fig. 7 and *B* in Fig. 10 will be as follows:

When the subscriber at station *A* removes his receiver from the hook, he will establish a circuit from the grounded terminal of battery 1 over the metallic circuit of the telephone line, through the winding of relay 2 to the negative side of battery 1. Current flowing in this path will cause the energization of this relay, thus establishing a second circuit through the winding of relay 3.

The energization of the latter will allow alternating current from generator *G* to pass through the winding of driving magnet 4, thus stepping forward the wipers of the switch, so as to engage contacts of the switch bank. The connections of the off-normal springs *O N* will be changed as soon as the wipers have taken the first step from their normal position, and hence contacts *c* and *a* will be broken and *c'* and *a'* closed. It will be seen that as soon as these changes take place the circuit over which relay 3 was energized will be broken at contact *c*, and hence that this relay will then depend for its continued energization upon the condition of the contacts over which the private wiper *P* is passing. The bank contacts of this switch are multiplied with the bank contacts of other line switches and are connected to first selectors. When a first selector switch is in use, its private contact will be connected to ground as will be described later. If then, the first private contact is grounded when wiper *P* reaches it, relay 3 will remain energized and the driving magnet will step the wipers ahead until a second contact is reached. If this contact is not connected to ground, relay 3 will fall back to normal, thus breaking the circuit through the driving magnet 4 and the wipers *L'*, *L*² and *P* will come to rest upon contacts *b*, *b'* and *b*² respectively. When relay 3 becomes de-energized, a circuit will be closed through contact *x* of relay 2, closed contact *c'* of the off-normal springs, back contact *c*³ of relay 3, and the winding of relay 5. Current flowing through the winding of relay 5 will cause it to attract its armature, thus opening the circuit which previously existed through the winding of relay 2.

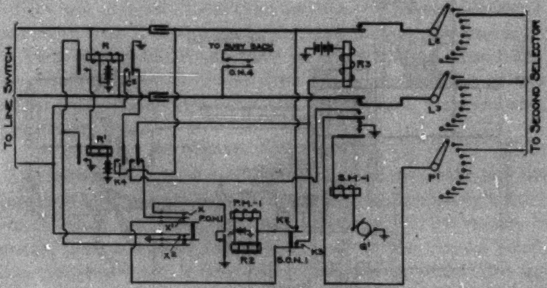

FIG. 8.—First selector

This latter relay would fall back immediately were it not for the fact that it is a slow releasing relay. The instant that relay 5 is energized, relay R of the first selector (Fig. 8) will attract its armature, due to current flowing through its two windings and the subscriber's line and instrument in series, thus causing the energization of relay R' and connecting ground through contact c^3 to contact b^2 on the line switch, and preventing other line switches from connecting with this first selector. The energization of relays 5 and R is accomplished in a small fraction of a second and relay 2, although the original circuit through its winding was opened by relay 5, remains energized over a second circuit which extends from battery 1 through its winding, contacts c^2 and c^4 private wiper P, bank contact b^2 to ground at the armature of relay R.

The calling instrument will then be connected to a first selector, and the subscriber will proceed to set up on his calling device the number of the station desired, for example 5472, and turn the starting lever. Contact K will then be opened and closed five times while contact K' remains closed, thus preventing the subscriber from receiving a disagreeable click. Each time the circuit is broken and closed in this manner, relay R of the first selector will be de-energized and energized and a circuit will be established five times momentarily from ground at the armature of relay R, through contact K^4 of relay R' contact K^2 of the secondary off-normal, thence through relay R^2 and the horizontal or "primary" magnet, $P\,M - 1$, in multiple to the negative or non-grounded side of battery. The relay R^2 will attract its armature the instant current flows through its winding, and as it is of the slow-release type, its contacts will remain open during the make and break periods of relay R, and the primary magnet $P\,M - 1$ will force the wipers of the switch forward one step, in the horizontal direction, for each current impulse. After the impulses cease relay R^2 will fall back and current will flow from ground through the contact of relay R^2 and the primary off-normal contacts x and x', (the three springs which form these contacts will be bunched at all times when the switch is out of its normal position) through the secondary off-normal K^3 to the negative side of battery through the winding of relay R^3. The energization of this latter relay will close a path for alternating current from generator G' through the winding of the vertical or "secondary" magnet $S\,M - 1$ to ground, thus causing the switch wipers to move vertically and hence to engage the bank contacts. As soon as the switch makes one vertical step, off-normal contacts K^2 and K^3 will open and relay R^3 will depend for its continued energization upon the condition of the contacts over which private wiper P^1 is passing. As soon as this wiper rests upon a contact which is not busy and hence ungrounded, the flow of current through the [illegible]y R^3 will cease, thus breaking the circuit through the secondary magnet, and the switch will come to rest. The circuit from the subscriber's instrument will then be continued to a second selector. The falling back of relay R^3 will place a ground upon wiper P', thus rendering the second selector busy and preventing other first selectors from being connected with it. This ground connection will also cause the energization of relay R^4 of the second selector.

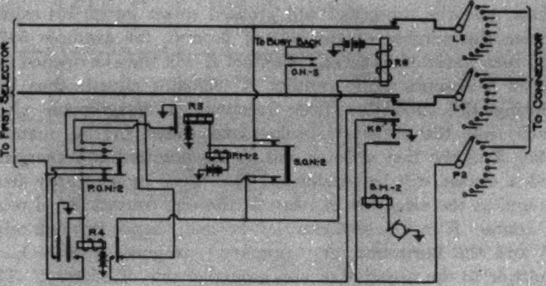

Fig. 9.—Second selector

After these circuit changes have taken place, the subscriber's calling device will break and close the line circuit four times, and again relay R of the first selector will be de-energized and energized. At this time, however, the circuit through the primary magnet $PM-1$ of the first selector will be open at the secondary off-normal contact K^2, and circuit changes similar to those which took place at the first selector will occur at the second selector (Fig. 9). When relay R^6 of the second selector falls back after an idle contact has been located by the private wiper P^2 the calling line will be connected through the line wipers L^5 and L^6 to the connector, and a ground connection will be placed upon the private wiper P^2 which will render the selected connector busy and establish a circuit through which relay R^7 of the connector will be energized.

When the calling device causes the de-energization and energization of relay R of the first selector for the third time, the primary magnet $P\ M - 3$ of the connector (Fig. 10) will move the wiper seven steps in a horizontal direction, while the slow-acting relay R^8 will retain its armature in the attracted position. When the impulses cease and relay R^8 is restored to normal, relay R^9 will be energized over the path which begins at ground at the primary off-normal contact $P\ O\ N - 3$ and extends through contacts K^5 and K^6, the winding of relay R^9 to battery. As soon as relay R^9 is energized, contact K^7 will be closed and K^6 broken and hence this relay will depend for its subsequent energization upon current flowing from ground through contact K^8 of relay R^6 of the second selector. The energization of relay R^9 will cut the primary driving magnet out of circuit and in its stead place the secondary magnet $S\ M - 3$. This is the condition of affairs which will exist when the last set of impulses, two in number, is sent from the calling subscriber's station. The secondary magnet $S\ M - 3$ will give the switch wipers their vertical movement while relay R^8 will be energized a second time and locked, while the impulses are being sent, through its own contact K^{13} (contact K^{19} of the secondary off-normal opens with the first vertical step of the wipers) and assume its normal position as soon as the flow of interrupted current ceases.

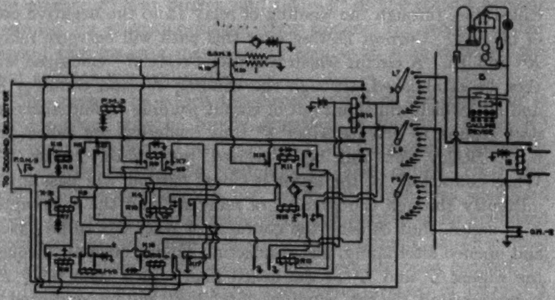

FIG. 10.—Connector

At this stage of the proceedings one or two things will happen, depending upon whether the called line is busy or not busy. If busy, the private contact upon which wiper P^3 rests will be connected to ground at the off-normal contact $O\ N - 2$ or at a second connector which is connected to the called line. As a result relay R^{10} will remain inactive and the busy-back signal will be given to the calling subscriber. The circuit over which this signal is given may be traced from ground at the busy-back induction coil I, through contact K^{20} of the secondary off-normal $S\ O\ N - 3$ contact K^{16} of relay R^{11}, to one side of the talking circuit, thence to ground through one winding of relay R and also over the subscriber's line and through the second winding of relay R. If, on the other hand, the line is not busy when the wiper P^3 reaches its private contact, current will flow from the positive pole of battery at contact K^{17} of relay R^{16} through contact K^9 of relay R^7, contact K^{10} of relay R^8, winding W of relay R^{10} to the private wiper P^3, thence to the private contact of the called line, through the winding of relay 15 to the negative pole of battery. Current flowing over this path will energize relays R^{10} and 15. A circuit which maintains relay R^{10} energized will then be established, through the winding W^1 and contacts K^9 and K^{21}, which will shunt out of circuit winding W and also connect ground to private wiper P^3 thus rendering the called line busy. Relay R^{11} will be energized immediately after R^{10}. When contact K^4 of the latter is closed current will pass intermittently through the winding of relay R^{12} and the interrupter T in series, thus causing the contacts of relay R^{12} to be closed and opened alternately, and connecting ringing current through the wipers L^7 and L^8 to the called line. Each time relay R^{12} is de-energized, the two windings of relay R^{13} will be connected to the line, so that current will pass through them when the circuit is closed by the removal of the called subscriber's receiver.

When, in response to the ringing of the bell, the subscriber answers, relay R^{13} and hence R^{14} and R^{16} will be energized, and the instruments of the calling and called subscribers will then be connected together for conversation. Talking current for the latter will be supplied through the winding sof relay R^{13} while the calling subscriber will receive his supply of current from relay R of the first selector.

When conversation has been finished and the called subscriber hangs up his receiver, he will cause the connector switch to be released and restored to normal, while this same act on the part of the calling subscriber will restore the line switch, the first selector and the second selector. The control of these three switches rests primarily with relay R^1 of the first selector. When relay R is restored to normal R^1 will also be de-energized, and current will flow through the winding of relay R^3, causing the latter to attract its armature, thus closing a circuit for generator current through the secondary magnet $S\,M-1$. The latter will then drive forward the wipers of the switch and when the contacts of off-normal $P\,O\,N-1$ are opened, the circuit which has previously existed through R^3 will be opened and the first selector will be in normal position.

When the off-normal contacts $P\,O\,N-1$ resume their normal positions contact x^3 of the first selector will be opened and therefore relay 2, and hence relay 5 will return to normal position. The de-energization of the latter will restore the line switch wipers to normal.

When relay R^3 became energized, the circuit from ground over the private P^1 was broken and relay R^4 of the second selector assumed its normal position, thus causing the release of the second selector in a manner very similar to that in which the first selector was restored.

The method by which the disconnection of the connector is accomplished may be briefly described as follows: Relay R^{13} will resume its normal position the instant the circuit is opened at the called subscriber's switchhook. The cut-off relay R^{14} will then be de-energized but relay R^{15} which was energized when the called station responded, will remain in its energized position due to current flowing from ground at off-normal $P\,O\,N-3$ through its winding and normally open contact K^{15} to battery. Therefore, upon the de-energization of relay R^{14}, relay R^{15} will attract its armature, thus allowing alternating current to flow through the secondary magnet $S\,M-3$ and also placing ground upon the private contact and preventing the connector from being selected during the time of release. As soon as the primary off-normal contact is restored to normal, relay R^{15} will fall back and open the circuit through the secondary magnet. The switch and all relays have then assumed their normal position. If the called subscriber does not respond the control of relay R^{15} and hence the release of the connector switch will remain with the calling subscriber.

If, at the time a subscriber removes his receiver from its hook, each one of the 10 first selectors connected to the line switch is busy, the wipers of the switch will stop upon the eleventh contacts. As the eleventh private contact is dead, relay 3 will fall back and relay 5 will be energized as it will when the wiper P rests upon a contact of an idle trunk. However, there is provided on this switch a special off-normal contact *S O N* which is closed only when the wipers are in the eleventh position. In this case, therefore, as soon as relay 5 becomes energized, a path for current through relay 2 is again established over the subscriber's line, through the wiper L^1 to ground at the eleventh contact. A connection from the busy-back induction coil is brought to the contact upon which wiper L^2 rests and hence the subscriber will be notified that he cannot immediately obtain a connection. As soon as he hangs up his receiver, relay 2 and hence relay 5 will be de-energized and the switch will be restored to normal.

The first and second selector switches are each provided with off-normal contacts ($O N - 4$ and $O N - 5$ respectively) which will cause the busy-back signal to be given to a calling subscriber when the wipers of a switch have made eleven vertical steps, as will be the case when all of the ten trunks in a group are in use.

In nearly, if not in all existing automatic exchanges, battery current is used for driving the selector wipers to select an idle trunk. In some cases a break contact on the driving magnet interrupts the current, and in others an individual interrupter, which serves a number of switches, is used. As already stated, the system described contemplates the use of alternating current. It is the intention to use current of approximately 20 cycles and as a result the wipers will pass over the trunk contacts at the rate of 40 contacts per second. Therefore, in the case of the line switch one-quarter of a second will be required for the wipers to pass over an entire bank of ten contacts, and this speed is so great that there is no danger that the subscriber will operate his calling device before the trunk has been selected.

AUTOMATIC-DISTRIBUTING SWITCHBOARD

As no automatic-distributing system has been placed in operation, it is interesting only for its future possibilities. A multiple switchboard which is similar in appearance to a manual multiple switchboard will be used. No answering jacks or answering lamps are necessary and upon the key and plug shelves single plugs will appear instead of pairs of plugs. Switches, which may be of the same general construction as selector switches used in automatic switchboards, are required and at each subscriber's station will be a common battery telephone of the ordinary type, no calling device or additional apparatus being necessary.

In making a call the subscriber will remove his receiver in the regular manner, and by so doing will light a lamp associated with one of the plugs upon the keyshelf at the operator's position. It will be understood that switches similar to any one of the five selector switches already described and either an individual line switch or a back-selecting arrangement can be employed to continue the subscriber's line to the switchboard. The operation of a line relay in the back-selecting scheme will set in motion two separate switches, one will connect its wipers to the terminals of the calling line, while the second will select an idle cord at the first idle operator's position. When both of the switches have come to rest, current flowing through a relay over the subscriber's line will cause the illumination of a lamp on the keyboard in front of an operator. The operator will throw the listening key associated with this lamp and ascertain from the subscriber the number of the station desired. Having received this information, she will, without testing, insert the plug into the multiple jack of the desired line, extinguishing the calling lamp and lighting in its place a second lamp which acts as a supervisory. If the line is not busy, the bell will then be rung automatically until the subscriber responds, when the supervisory lamp will be extinguished. If the line is busy when the connection is established, the subscriber will receive the busy signal and upon hanging up will give the disconnect signal to the operator.

At the end of conversation when the two subscribers have placed their receivers upon their hooks, the supervisory lamps will light and the operator will withdraw the plug from the multiple jacks, thus restoring the switches as well as all other apparatus to normal position.

With this scheme a subscriber's line is not associated with one particular line lamp, as in the case of manual switchboards, but any subscriber may light any calling lamp in front of any operator's position. When a call is made, if no cords are in use, the first idle lamp in the first operator's position will be lighted, while a second call will come in upon the lamp of the next cord in the same position, and so on until all cords at the first position are in use. Additional calls will then automatically pass to the second position. In this way one operator can handle all calls at certain times of the day and when business increases a second operator can take up her duties, then the third and as many as may be necessary. It is not necessary at the time of light load for an operator to change from one position to another or to answer calls in multiple jacks as the automatic apparatus provided makes it unnecessary. It can readily be seen from the facts just stated that inasmuch as the operators work more efficiently than at a manual multiple switchboard, each operator can handle a greater number of calls, thus reducing the total number of operators required, and as a result the total number of switchboard sections. These are the advantages claimed for this system. If it is to be a success, the advantages must be great enough to outweigh the disadvantages due to the use of automatic switches, as well as to the initial cost of the equipment which is considerably more than that of a manual switchboard.

SEMI-AUTOMATIC SWITCHBOARD

Operators are also required in a semi-automatic switchboard but instead of using multiple jack equipment as in the automatic distributing, each operator is provided with a desk and apparatus which enables her to receive calls from subscribers, to operate selector and connector switches and thus establish connections between lines. Either individual line switches or a back-selecting scheme can be used to connect calling lines to the trunk circuits. The method of operation, using the back-selecting scheme, is as follows:

When a receiver is removed from its hook, the operation of the corresponding line relay sets in motion a line selecting switch which selects the calling line, and a second switch which selects the first idle trunk terminating at the position of the first operator having an idle trunk, thus connecting the calling line through these two switching circuits, and lighting a lamp in front of that operator. The operator's desk is equipped with two or more trunk circuits, each requiring a listening key and two, three, four, or five rows of ten keys each for operating the switches—the number of rows depending upon the size of the exchange. That is, if an exchange has an ultimate of 1000 lines, three rows will be required, while four are necessary for a 10,000 line system and five for a 100,000 line system. When the lamp associated with a group of keys lights, showing that a connection is desired, the operator will, by means of the listening key, place her telephone set in connection with the calling line. After ascertaining from the subscriber the number of the line desired, she will operate the proper key in each of the groups, thus setting up the number of the called line. Immediately after the key corresponding to the first digit is operated, current passing through an interrupter, which is individual to the trunk circuit, will operate the first selector associated with the line selector, and immediately thereafter a second impulse through the key corresponding to the second digit will operate the second selector, and in the case of 10,000 line system, a third and fourth impulse will complete the connection through the connector to the called line. As soon as the last impulse has been sent to the connector, the lamp on the operator's keyboard will be extinguished and the trunk over which the preliminary connection to the operator's desk was made, will be disconnected and placed in condition to receive a second call. The bell of the called station will be rung automatically and at the end of conversation the switches will be disconnected, without the assistance of the operator, when the subscribers hang up their receivers.

It is easily seen that many variations in the method of operation of semi-automatic can be made and that there is a wide field for argument as to the importance of certain features. It will be noted, for example, that in the operation described, the operator is disconnected from the subscriber as soon as the last impulse has been transmitted to the connector. Hence, if the attention of the operator is again desired by the subscriber, for any reason, the operation of the switchhook may place him in communication with a second operator, thus causing possible confusion and dissatisfaction.

It is probable that before many years the differences of opinion which now exist as to the relative advantages of manual and automatic will disappear, and that definite standards will be adopted for the various conditions of practice. It is possible that for localities of a certain size one system will be used while for larger and smaller installations entirely different systems will be found to meet the requirements more satisfactorily. It is now impossible to foretell what this ultimate solution of the problem will be, and one who is bold enough to attempt to do so is putting his reputation as a prophet to a severe test.

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THE SEMI-AUTOMATIC METHOD OF HANDLING TELEPHONE TRAFFIC

BY EDWARD E. CLEMENT

It is the purpose of this paper to describe briefly the Clement automanual telephone exchange system, explain its principles, and show some of the results it has produced. For proper presentation, and in order to make necessary comparisons, the subject will be developed as follows:

1. The limitations and waste necessarily involved in manually operated exchange systems.
2. Characteristic features and limitations of automatic methods.
3. The principles involved in the automanual system, and the manner in which they are applied to avoid waste, and secure increased economy and efficiency.

Manual System

Some years ago it was generally agreed among telephone engineers that the limit of concentration had been reached in the 10,000-line multiple switchboard. It is true that switchboards of a much greater capacity than this had been designed and some of them built, but other reasons beside the mechanical and physical limitations of the central office equipment forbid extreme concentration. Among these the most important factor is that of the increasing ratio of non-earning investment in the cable and wire plant. It is unnecessary for me to recapitulate the figures that have been presented from time to time before the Institute, in support of this statement. It has been shown, and I believe is not disputed, that over 90 per cent, and in some cases 98 per cent of the wires are idle, on the average, during the

24 hours; and in well-designed systems observation has shown that the total number of connections established or in course of establishment simultaneously at the peak of the load is not more than 40 per cent of the number of sets of connective apparatus necessarily provided. This percentage of course does not refer to line terminals, of which the percentage is only a fraction of this. Since the wire and cable plant represents a large proportion of the entire investment in any existing system, either manual or automatic, it will be seen that important as the switchboard limitations are, their effect in determining the engineering policy is only contributory.

In subdividing the manual switchboard system to reduce cost, another element of expense is introduced which tends largely to offset the advantages of the subdivision. I refer to the necessity for trunking with all of its attendant problems, including the provision of extra trunk operators and the difficulty of maintaining the standard of efficiency as high as it would be in a single switchboard exchange. The maximum efficiency possible with strictly manual equipment is reached in the single switchboard exchange serving less than 10,000 lines and probably not to exceed 8,500. (This contemplates of course the use of substantial plugs and jacks, which are impossible in larger switchboards).

For purpose of comparison, and bearing in mind the established standard of efficiency, it may be well to note here the necessary steps in manually effecting a connection of two lines. Assuming modern equipment with so-called automatic ringing and centralized battery, the subscriber calls by taking down his receiver from the switch-hook, which automatically lights the line lamp. The operator notes the signal, picks up the answering plug and inserts it in the jack corresponding to the lamp; then throws over her listening key and inquires the number; picks up the calling plug and advances it selectively to the multiple jack of the wanted line; touches the plug tip to the jack thimble for test and notes the result; if line is idle inserts the plug; closes the listening key; presses down the ringing button; observes whether the called party answers; supervises the connection; finally removes the plugs and restores them to their seats. Should the line wanted test busy, the calling plug is not inserted, and the operator either advises the calling subscriber of the fact, or connects the busy-back signal. For party-line ringing an additional act is the selection of the ringing button.

This statement covers the duties of a subscribers' operator on a board having no trunking. The use of trunks introduces not only complication, but uncertainty and delay. In most manual systems the subscribers' or *A* operators communicate with the *B* operators over order wires, which requires the *B* operators after receiving the numbers to answer back and designate the trunks to be used in the connections. Uncertainty results, because the chances for error are obviously multiplied, and delays result which are equally obvious, since each trunk connection must go through two operators. Both the delays and the uncertainties affect the efficiency of the equipment and lower its earning power, as well as the efficiency of the service. Observation has shown that a very large percentage, rising as high as between 80 and 90, of all irregularities reported is due primarily to the trunking system. As an example of cost, in the West Exchange of the Kansas City Home Telephone System, the cost of handling trunked calls, amounting to 25 per cent of the total traffic, is over 31 per cent of the entire operating expense chargeable to that particular exchange. As the Kansas City Company has an economical schedule in vogue, this percentage is fairly illustrative of the condition in general.

The limit of subdivision in the manual system is reached when the saving in interest charges on the investment in the centralized cable and wire plant is balanced by the losses due to the increase in operating expense and the lowering of efficiency of operation due to trunking. To make this clear, it should be understood that in providing for traffic between switching centers or exchanges, the number of trunk pairs required bears no definite or fixed relation to the number of lines, but varies with several factors which must be determined for every plant. Assuming a minimum average number of trunks, bearing the same percentage relation to the total number of lines that the total load or number of simultaneous connections would bear at the peak, there would of course be a very large saving in first investment, but it would have to be effected by a perfect subdivision of the system into districts or sub-centers which would bear a fixed and invariable average relation to each other. Perfect subdivision of this kind is only theoretically possible, and it can very readily be shown that a saving by subdivision of say 30 or 40 per cent, in a large exchange carrying a heavy traffic load, in most cases would be offset by the increase in operating expense. For example, reference may be made o conditions in New York, where the trunking runs to over 90 per cent in certain exchanges. In Detroit, the average trunking percentage for all the exchanges was recently figured over 55. A subscribers' or *A* operator in these exchanges cannot average over 185 calls per hour, while the *B* operators would average about 350 in the busy hour and the general average for 24 hours would be under 180 per *A* operator-hour. The effect of the high percentage of trunked calls is apparent when this is compared with the operators' averages in exchanges where the trunking percentage is zero. In such an exchange an *A* operator working under the method I have outlined can handle between 280 and 290 calls in the busy hour and the average for 24 hours would be about 175 per operator-hour. This will be referred to again, in connection with the diagrams and tables.

Next to the limitation imposed by the necessities of trunking, the arbitrary arrangement and grouping of subscribers' lines on the *A* positions must be considered. The switchboard is divided into sections to which all the lines are multipled with three operators' positions per section arranged so that any one of the operators can reach a multiple or calling jack of any line entering the exchange. For answering purposes each position is equipped with a certain number of answering jacks with their accompanying signal lamps. The distribution of the lines among these answering jacks is arbitrary, and determined empirically by the requirements of the service. Inasmuch as no fixed and invariable rule can be laid down covering the percentage of calls originating in a given time in any one group of lines, obviously the number of answering jacks, or the number of lines to be handled by each operator, must be limited approximately by average or normal traffic conditions in the busy hour. In the Louisville Home Exchange, for example, where the average is 18.2 calls per line per day, the average number of lines per operator is about 105, and these are all individual lines, no party-line service being given. In the Bell Exchange at Detroit, where the load is very heavy, the calls averaging over 22 per line per day, the number of lines per operator is about 90. The development of party-lines is about 60 per cent. The Louisville exchange serves 10,000 subscribers, with six per cent trunking, and an average of 182,000 originating calls per day of 24 hours. Assuming that there would be 16,500 calls during the busy hour, if perfect distribution among the operators could be obtained, without otherwise changing the character of the switchboard, a maximum number of 57 operators only would be required in the busy hour instead of 63 or a saving of about 10 per cent.

A number of schemes have been suggested for securing this or a greater saving, all depending on the same fundamental principle of automatic intermediate distribution, by the use of a traffic distributor. That none of these schemes have gone into general use is at least a persuasive argument that this sort of distribution is recognized as a mere makeshift, and of itself is not attractive in view of the expense of its installation and the retention of the other objectionable features of the manual board.

In considering the figures given for this distribution, and its effect on the number of operators, it should of course be borne in mind that below a certain point on the load curve there is a loss of efficiency in any system, reached when the total load falls below the capacity of one or two operators to handle. This loss would be minimized however by the concentration of all calls at one part of the board when the load is very light, the effect being to save patrolling, which must be practiced at present, since calls may come in on any position.

The limitations of the manual board may be briefly summarized as follows: (1) the necessity for each act required in establishing and taking down a connection to be performed by the operator " by hand "; (2) the arbitrary and empirical grouping of lines on answering positions; (3) the small number of lines (relatively to the size of any well-settled district to be served) which can be concentrated at one operating center and handled by one group of operators, due to the mechanical limitation of space for multiples, and the cost of the cable and wire plant; (4) the great loss in efficiency, increase in operating expense, and depreciation of the investment in the multiple portion of the switchboard, as the percentage of trunked calls rises.

The existence of these limitations is generally recognized by companies operating manual boards, but not their extent. Traffic men know that at the very peak of the load in any exchange the number of plugs and cords in simultaneous use rarely exceeds 33⅓ per cent of the total number provided, which means an over-provision of 200 per cent of connective apparatus, with its attendant keys, signals, relays, etc., necessitated by the fact that one group of lines may be very busy while another group is comparatively idle. Some companies, where the trunking percentage exceeds 85, omit the multiples entirely from their *A* boards. The cost of these multiples constitutes a very large percentage of the total cost of the board, and this cost is not justified when their maximum possible efficiency (which is low in itself, due to other factors,) is reduced by something like 85 per cent; but their omission increases operating expense, and introduces additional error, because it necessitates the trunking also of the remaining 15 per cent of calls, giving really 100 per cent trunking.

Apart from the first cost and the expense of operating, the cost of maintenance on a manual switchboard is out of all proportion to its efficiency. A vital part of such a switchboard is the equipment of cords and plugs, and the renewal of cords requires constant attention and causes continuous expense. Moreover, it needs only a moment's reflection to appreciate the effect of defective cords on total efficiency of the service, and in part on its most vital feature, that of transmission. A cord commences to depreciate the moment it goes into service, and in spite of renewals, the cords along the board can never be at 100 per cent efficiency as compared with other portions of the circuit. Inasmuch as every conversation takes place through some cord, it follows that so much of the transmission as depends upon cord efficiency can never equal that through other portions of the circuits consisting of solid wires and the good metallic contacts of well made plugs and jacks, and keys.

AUTOMATIC SYSTEM

Turning now to full automatic methods, we recognize that a number of the limitations and disadvantages of the manual switchboards are thereby eliminated, but others are added which are unavoidable, even in the best automatic systems. It is true that the full automatic system is much more flexible than a manual system could be, permitting subdivision to an extent which in manual practice is impossible, and it is also true that the operator factor is to a certain extent reduced. It is equally true, however, that there are mechanical and electrical limitations to subdivision, that a certain number of operators are unavoidable and constantly required, that the first cost and cost of maintenance of a system are considerably increased by the location of sending devices at all subscribers' stations, and that a meretricious and contradictory method of operation is adopted, which in itself constitutes not only a departure from sound fundamental principles, but also a limitation, felt in proportion to the diversity of and increase in miscellaneous traffic. To put this in a word, the human element which is indispensable to the rendition of good service, whether by mechanical or other means, is removed from contact with the calling subscriber, who is forced to do his own operating.

A certain percentage of operators have been found indispensable, however, in all automatic exchanges of any size. Pay station lines, many branch exchanges, trunk positions for branch exchanges, trunk positions for long distance, and the like, all require operators just the same as they do in the manual systems, and in addition a certain number of persons, whose functions are not always clearly suggested by their titles, are and of necessity must be employed to render first aid to the injured, or otherwise stated to connect themselves to lines which have difficulty in mechanically effecting selection of other wanted lines, and either digitally or electrically assist the switches to perform their normal functions. Off normal lamps and various types of trunk signals, when supplied, together with the keenly trained sixth sense of these persons, enable them to locate apparatus which is not properly working, and having some expert duties, it may safely be assumed that in every exchange their average pay is at least $60 per month, which is double the pay of a good manual operator.

In certain typical automatic plants, notably one serving 10,000 subscriber lines in a large city in Ohio, without any party line service, the number of these mechanicians is on a basis of one for every 700 lines. Taking these as equal to double the number of ordinary operators in point of wage, we have the equivalent of about 29 ordinary operators, serving 350 lines per operator. In addition to the automatic equipment, a manual switchboard is provided at which the operators handle private branch exchange trunks, pay station lines and the like. At all but five of the private branch exchanges manual operators are employed. The use of manual equipment supports the previous statement, and moreover the automatic equipment is concentrated, and the manual equipment is subdivided, so that to a large extent the peculiar advantages of both are lost. It should be here stated that in the plant referred to, out of 83 private branch exchanges 78 are equipped with manual switchboards handled by local operators, and only five are fully automatic.

These figures are rendered more significant by the fact that the traffic originating in private branch exchanges in any city is far in excess of the average calls per line throughout the rest of the system. Thus the largest users of the service in this system are handled by manual methods practically to the exclusion of automatic.

The sending devices or dial machines located at all the subscribers' stations in any automatic system are objectionable for three reasons: the first is the original cost; the second, added cost of maintenance and increased liability to derangement and consequent poor service due to instrument defects; and the third, the uncertainty in transmission of controlling impulses for switches, over lines of varied length and resistance, which moreover are exposed to varying external conditions.

The simplest form of subscribers' sender is a dial or equivalent key controlling a pair of contacts in the metallic circuit. It need scarcely be pointed out that this insertion of another contact in the talking circuit is in itself a detrimental feature. Passing this however, and without criticism of specific designs of senders, it may be stated that the first cost of the sender, plus the investment represented in interest by the annual maintenance charge added thereby, more than doubles the cost of the subscribers' equipment, as compared with a simple manual common battery telephone set. The increase in cost alone of a fully equipped automatic telephone over corresponding types of manual telephones is more than 50 per cent allowing nothing for added maintenance.

Again, the repeating relays which respond to line impulses and directly control the switches, must be balanced against their respective switch operating magnets. As these relays are forced to work on current impulses transmitted through lines of varied length and resistance and with many different senders, it is apparent that the working must be to some extent marginal, especially between widely separated centers.

MANUAL VS. AUTOMATIC OPERATION

The subscriber in the manual system is sold service, there being a difference in degree only and not in kind, between this service and that rendered by a messenger company. The first requirement for such service is special capacity, and for this training and discipline are both indispensable requisites. A messenger company trains its employes, and the manual telephone company trains its operators, and in addition maintains discipline almost military in its strictness. But the requirements made of an operator in handling common battery manual switchboard appliances are but little more exacting or onerous than those imposed in the handling of his calling dial and the manipulation of ringing button, on the automatic subscriber, who has no advantage of acquired poise and methodical habit, as have the manual operators. However, the question of efficiency only in the purely mechanical work of handling apparatus cannot be considered without taking into account the mental attitude of the subscriber toward an agency which has already passed beyond the realm of luxury, and become an absolute daily dependence in every function of social and business life. Taken in the mass, subscribers must, and observation shows they do, look upon the telephone company not in any case as an aggregation of mechanism, but as a responsible medium and agency to which they can safely entrust a certain portion of their business. This attitude becomes insistent as social relations become closer and more complicated with their increase. The question is therefore one of policy as well as mechanical possibilities.

For the specially trained and poised manual operator, the automatic method substitutes the untrained, undisciplined subscriber exposed to conditions so variable that they are responsible for a considerable percentage of the errors and reported troubles in even the best manual systems. Uniform and efficient operation of mechanism under such conditions is problematical, and no fair test has yet been afforded on a sufficient scale, and with a widely enough extended full-automatic area to furnish satisfactory affirmative arguments for the principle of subscriber-operation.

The saving effected in operators by the use of a full automatic system, it may safely be assumed from the facts herein stated, is only a percentage saving which varies with traffic and other conditions, but would probably never exceed 50 per cent under the most favorable conditions, even allowing for the switchboard men and other skilled employes in the manual exchange (since operating and maintenance must involve a certain amount of expense in all systems.) Against this saving are to be set interest on the extra first cost and the additional maintenance on the subscribers' instrument equipment, due to the addition of senders. This cost in a 10,000 line exchange may be estimated at not less than $25,000, and the extra maintenance charge at not less than $5,000, or a total annual figure of not less than $6,250, not including depreciation. The depreciation factor is relatively high, because the subscribers' sender is not only exposed to constant use, but unskilled use and accident as well. Reports show sender trouble as high as 65 per cent of all instrument trouble. The figure given may therefore be regarded as conservative. The salaries of 80 operators, at an average of $25 per month would be $24,000 a year, so that more than 25 per cent of the saving in operators' salaries is represented by the additional outlay for the subscribers' automatic equipment alone.

The point to consider therefore is whether a reduction in operating expense, assumed at an unabsorbed maximum of 37½ per cent, is sufficient to justify depriving the subscribers of any direct access to human intelligence, slowing down the service, rendering it uncertain, and finally removing the principal ground for confidence on the part of the subscribers. In an exchange like that above mentioned, where a large percentage of calls is handled manually in any case, the reduction would undoubtedly be much less than this figure. Another point is that the constant growth and expansion in any territory must lead to more complicated operating conditions, and a consequent increase in the percentage of enforced manual operating.

It is generally accepted by traffic men and engineers that the most important step in handling traffic is to effect quick and satisfactory initial connection of a calling subscriber with the central office agency, of whatever nature. In a manual system, it may be taken as axiomatic that if a subscriber is given quick response to his calls, subsequent delays are secondary in their effect, but delay in answering is fatal to good service, because it immediately destroys the subscribers' feeling of confidence. It is at least partly to meet this condition that the provision of the so-called mechanicians is made in the automatic exchange, which in meeting one objection creates another, because the claim of secret service cannot be supported when a force of employes is provided regularly equipped for the express purpose of listening in when the switches do not work properly. It is no answer to this objection to say that eaves-dropping is possible in any system; because unwarranted listening-in is rare where it is not within the regular province of employes, and where proper discipline is maintained. Even in the manual exchange, if the operators are required to supervise connections by means of their signals, the occasion and opportunity for eaves-dropping are lacking. Moreover, this condition is provided for in modern manual systems by means of a special signal lamp connected with the listening keys of each position, and under constant observation of a monitor. The flickering of this lamp indicates routine work, but its steady burning enables the monitor to cut in her telephone on the corresponding position and at once detect any eaves-dropping. The provision of such supervisory means for peripetetic and unattached employes would be difficult if not impossible and certainly very inefficient.

In considering this whole question of human agency *vs.* answering machine, due regard must be paid, it should be repeated, to the manifold complications constantly arising in modern traffic, which if a high standard of efficiency is to be maintained, require human intelligence. Any method which is based on the assumption of 100 per cent normal operating conditions must fail to satisfy actual conditions in practice, and even granting for the sake of argument that such normal conditions prevail in the service of business districts during a part of the time, this takes no account of the uncertain character of residence communications, where the discipline due to general business experience and training is unavoidably lacking. A calling subscriber whose condition, or environment, or time, prevents his giving intelligible instructions to an operator, in a deliberate and normal manner, would certainly not be able to operate mechanism normally. In the automatic system misguided operation must extend its effect not only to the line calling but to the lines of other subscribers, and there is no means of detection unless the subscribers who have been annoyed call in to the information operator or trouble clerk, which in the majority of cases would not be done. In a manual system, after a wrong number is called, it is apparent to the operator, either by direct report from the subscriber or by her own observation, and this enables records to be made with some degree of accuracy, as well as a remedy for the trouble applied. Moreover, incomplete or defective instructions to the operator of a manual board, due to ignorance or mistake of the originating subscriber, are at once apparent, so that the call can be blocked, and further annoyance prevented. Take another example: Peg counts have been taken where there are competing systems in the same territory, showing that it is a frequent occurrence for calls to be made over one system for numbers in the other. Where one of these competing systems is automatic, and the other manual, such calls on the manual systems are readily blocked, but there are no means in the automatic system for blocking calls for numbers taken from the manual directory.

AUTOMANUAL SYSTEM

The fundamental principle underlying the Clement automanual system is this, that the calling subscriber should be met at once by the response of a human intelligence which can direct the proper automatic agencies to satisfy his wants; or in other words, that the correct method of handling telephone traffic is to sell service, and not rent apparatus. The analogy in this respect between a telephone company and a telegraph or messenger company is striking. Each is a conveyor of communications, and fundamentally it would be quite as correct for the messenger company to rent bicycles to its patrons, so that they might deliver their own messages, as to rent mechanism to telephone subscribers for the same purpose. The analogy extends even to the point of secret service, because if it were claimed that the renting of bicycles would enable patrons to deliver their messages secretly, then this claim would obviously be defeated by the provision of a corps of trained bicyclists for the express purpose of watching and helping distressed amateurs to their destination, in order to see that each message is correctly delivered.

FIG. 1.—Automanual operating equipment—Ashtabula Harbor

Stated broadly, the automanual is a combination of the manual and automatic methods which contemplates (1) centralization of automatic apparatus; (2) the employment and concentration of operators; (3) correct subdivision of a system for traffic handling.

I will amplify these three points a little before describing a typical system. First, the apparatus is all concentrated at exchange centers, the subscribers' lines and telephones being reduced to the naked common battery type, which is the limit of simplicity at present attainable in any system. The substation construction, and the connection and distribution of lines at the exchange centers are the same in the automanual system as they are in any modern standard common battery system. The method can be applied to magneto lines if desired, but this would only be called for now in the case of rural or toll lines. With regard to the operators, I have restricted them to the only indispensable and essential function requiring intelligence, that is, ascertaining the subscriber's want, and setting up a signal by which automatic apparatus may be caused to supply that want. The regular duty of a subscriber's operator permits no departure from this rule, since even emergency calls can be handled by switching them to another operator specially provided for such duty. The automanual operator works at 100 per cent efficiency all the time, and since her duties are simple and unvarying, she has the opportunity of becoming expert, and moreover, requires no tedious or expensive preliminary training. It has been found that one day's training will suffice for an automanual operator, as against three month's experience for manual operators to produce corresponding efficiency. The actual preliminary training period, before putting the operator in touch with subscribers, is about one-half hour for the automanual operator as against three weeks for the manual operator. The

FIG. 2.—Automanual operating room—Warren, Ohio

manual operator may require additional training if sent to a different exchange in the same city, where key board apparatus is different, as well as the arrangement of multiple; special training is also required to fit an *A* operator for the duties of a *B* position, or of a paystation operator. In the automanual, the method of operating is standard in all exchanges and under all conditions.

It is possible to concentrate all the operators at a single operating center, which can take care of all the switching or exchange centers in a district or even in an entire city, handling all calls with maximum efficiency, and giving uniform service regardless of the nature of the calls, or the time of calling, twenty-four hours per day. This concentration, and the distribution of the total load over a single group of operators, without regard to where the calls originated, effects great economies by eliminating all but the summatic load fluctuations, to which the total number of operators on duty is at all times directly proportional. A farther gain in efficiency is due to better discipline and control of the operators where they are concentrated. Perfect subdivision, within physical limits peculiar to each territory served, is possible with this system, and the benefits of operator-centralization are realized regardless of the extent of subdivision. In other words, I adhere to the rule of bringing the operator into direct communication with the calling subscriber, wherever

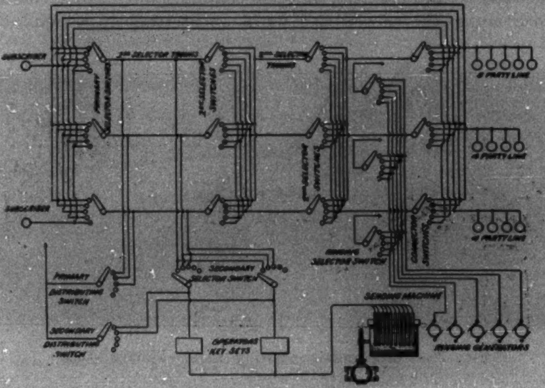
SUBSCRIBER
2nd SELECTOR TRUNKS
3rd SELECTOR TRUNKS
PRIMARY SELECTOR SWITCHES
2nd SELECTOR SWITCHES
3rd SELECTOR SWITCHES
5 PARTY LINE
4 PARTY LINE
4 PARTY LINE
SUBSCRIBER
RINGING SELECTOR SWITCH
CONNECTOR SWITCHES
PRIMARY DISTRIBUTING SWITCH
SECONDARY SELECTOR SWITCH
SECONDARY DISTRIBUTING SWITCH
OPERATORS KEY SETS
SENDING MACHINE
RINGING GENERATORS

FIG. 3.—General arrangement of automanual exchange

his line terminates. Moreover, no talking trunks or talking apparatus are tied up beyond the actual point of entry of the calling line until the operator's duties are concluded. I call this a " clearing-house system ", because all traffic is handled, directed and checked from the operating center or clearing-house, without any subscriber connections passing through the operating center. The cable plant between switching centers is designed with a sole view to traffic requirements between these centers, and without any regard to the location or connection of the operating center.

FIG. 4.—Switch

Fig. 3 is a simplified skeleton diagram showing the general lay-out of an automanual exchange equipment having a capacity up to 10,000 lines. In this diagram, five subscribers' lines are shown, one of which is a five-party line, two others are four-party lines, and the remaining two are individual lines. Ringing is supposed to be five party selective.

In this diagram, for the sake of clearness, only the most elementary forms of apparatus are shown. The switches, however, are supposed to represent two-motion, one-hundred-point, electromagnetically-driven, step-by-step automatic units, of uniform type, shown in Fig. 4. Percentage trunking is employed throughout the system shown, and the switches are equipped with banks (not shown in Fig. 4) containing ten vertical rows of ten contact pairs each. The motion is around and up, this, precedence of the rotary motion affording certain advantages, among which is the easy accommodation of row test-terminals, so that the two-motion switch can be used for primary selectors. This enables the entire system to be built up of interchangeable units.

FIG. 5.—100-line unit frames—Ashtabula

The method of aggregating units was adopted in the very beginning of my work, partly as a matter of convenience, but principally with a view to efficiency and economy in manufacture. It is followed in this manner: The individual or unit switch is composed of a certain number of interchangeable units, such as the spindle with its wipers, the frame, and interchangeable operating magnets; each switch or trunk circuit, such as the primary and first selector, the second selector and the connector equipment, is assembled complete as a unit, the latest designs having steel mounting plates upon which the unit switches with their relays, condensers, etc., are mounted and wired up complete, previous to being assembled on the racks; a sufficient number of switch plates, with the line and cut-off relays, lamp strips, and other accessories, are mounted on a frame section to form a 100-line unit; and finally these 100-line unit frames are aggregated to build up the full exchange equipment, adding thereto of course the operators' and wire chief's desks, power plant, etc. Five of these frames are shown in Fig. 5, which represents the Ashtabula equipment, with the wire chief's desk in the foreground. The operators' desks are in a separate room. Ten similar units are shown in Figs. 6 and 7, which show the Warren, O., equipment.

FIG. 6.—Automanual switch-room—Warren, Ohio., showing main frame and secondary switch panel

In Fig. 3, the circuits have been laid out so as to show in a simple way the analogy between this system and a manual switchboard system, the same operations being performed in the same manner throughout, but automatically instead of manually. For example, the subscribers' lines terminate on primary selector bank contacts which correspond to the answering jacks of the manual board, and they are also multipled to calling contacts in the banks of the connector switches, which correspond to the multiple jacks on the manual board.

The wipers of the primary selector switches constitute the equivalents of plugs which coöperate with the subscribers' answering jacks, but are mechanically driven thereto instead of by the hand of an operator. The first selector switches similarly correspond to the calling plugs of manual pairs, and the first selector trunks extending between the primary and the first selector switches are the equivalents of the cord circuits. The second selector and connector trunks are the same as trunk lines between different positions on a switchboard, the method of switching at each step corresponding to the selective insertion of another plug to add another link in the connection by a manual operator. The secondary selector switches constitute the equivalents of the operators' keys associated with the cord circuits, and the sending machine operated therethrough sends impulses to work the selector and connector switches, instead of spoken words to direct an equivalent number of successive operators. The primary distributing switch performs the function of the operator's mind in selecting an idle cord circuit for any given connection, and the secondary distributing switch is the equivalent

FIG. 7.—Automanual connecting-switch racks—Warren, Ohio., showing arrangement of 100-line units

of a monitor distributing calls among the operators, by directing each one of them when to answer.

The ringing selector switches take the place of the selective buttons of *B* or trunk operators so that the selection of the desired generator to ring a particular subscriber is directed by impulses from the sending machine, instead of by spoken words proceeding from the original or *A* operator. To complete the analogy, the releasing means for all the switches when in service are controlled by the connected subscribers, thus corresponding to the supervisory signals, by which in a manual system the subscribers can instruct the operators to clear out.

All subscribers' lines are represented by terminals in the primary selectors and in the connector banks, and while the method of trunking shown is only a contributory feature of this lay-out, the diagram will be fully described, for the benefit of those who may not be entirely familiar with this class of circuits. I might state in passing that there are a great many features of special design in the automanual circuits, but they involve so much detail that the limits of the present paper do not permit my presenting them at this time.

The progress of a call is from the calling subscriber through an idle primary selector, which becomes automatically attracted to his line, and thence through a secondary selector, similarly attracted, to an idle operator. Under no conditions is this departed from, even in subdivided systems. The principle is that the operator should be brought into direct touch with the subscriber at the very outset, precisely as in a manual system. Having ascertained the number, the operator sets up this number on her key set (Figs. 10 to 12) and sends impulses through her circuit to the first selector, second selector, connector, and ringing selector switches, thus establishing the wanted connection and also starting agencies in the connector circuit which continue thereafter automatically to ring until the called subscriber answers or the calling subscriber hangs up the receiver. After initiating the call, the calling subscriber's line is connected through the primary and secondary selector switches to the operator in every case, and, further movement of a subscriber's hook or the repeated opening and closing of the circuit, will not reach more than one operator, and cannot disturb general traffic conditions. A special busy tone-test is provided, brought into service through the first selector trunks so that it is audible to the operator when she comes in on a calling line if the calling subscriber has hung up his receiver. This happens sometimes through change of purpose or the like, and it is highly essential that the automanual operator should not experience the slightest delay, nor pay attention to anything except the rigid rule of getting the number and setting it up. After the operator has answered the calling subscriber is given full control of the connection, and can clear out and release all of the apparatus including the operator's set at any time up to the moment when the called subscriber answers. Thereafter, the called subscriber assumes control of the connector switch, which he can release so as to clear his line by merely hanging up his receiver. This prevents tying up the called line.

When the operator connects the sending machine to the switches, through her key set, impulses are sent in groups corresponding to the several keys depressed, that is to the number

FIG. 8.—Rotary switch

wanted, as well as to the number of the generator required to ring the wanted party, if it be a party-line. The first group of impulses steps around the first selector switch to pick out a group of second selector trunks, and an idle trunk in that group, leading to the wipers of the second selector switch. The second group of impulses works this second selector switch to pick out a group of connector trunks, and an idle trunk in that group, terminating on the wipers of a connector switch in whose banks appear the terminals of the wanted line. Successive groups of impulses are then transmitted to step the connector wipers around and up to the wanted line terminals.

Associated with each connector switch is an auxiliary or ringing selector, having a wiper sweeping over terminals which are connected to several ringing generators, as shown, each of which supplies current at a distinctive frequency. In actual practice, for five-party ringing, the frequencies are determined so that they cover about the same range as the older four-party harmonic frequencies, without the same liability to interference.

For these auxiliary selectors, in this and other parts of the system, a simple form of rotary switch is employed, shown in Fig. 8. The magnet unit in this switch is the same as the interchangeable units employed in the larger switch, and the wipers are always rotated in the same direction, being restored to normal or zero position by connecting an interrupter to the stepping magnet through a pair of extended arc contacts bridged together as long as the wipers are off normal.

At the last stage in a connection, when the wanted subscriber's line has been picked out by the connector switch, and the ringing selector has been set so as to bring into service the proper generator, that generator is then automatically and periodically connected by a ringing relay to the subscriber's line to ring his bell. At all other times the ringing selector remains disconnected.

The control of the primary selector switches is through relays on the switch racks, responsive to line current. These relays complete local circuits to place test potential on the row and individual test contacts of the primary selector switches, and at the same time close starting circuits for the primary distributors which select the idle trunks and for the secondary distributors which select the idle operators. A type of relay is employed both for the lines and switches, shown in Fig. 9, which is the result of much thought and experiment. This relay has the flux bar bent over at both ends, the inner end being screwed to the rack, and the outer end carrying the adjustment for the magnet core. The bell crank armature is dropped through a slot punched in the flux bar near the rack end, and the springs are mounted on this same end, so that both the armature lever and the springs extend forwardly. This construction gives a long leverage with a very small air gap which is essential for this class of work, and also exposes the core adjustment and spring contacts.

FIG. 9.—Relay

The operation of the secondary selector switches is essentially the same as that of the primaries. As soon as the primary distributing switch has determined the primary trunk to be connected to the calling line, the selected secondary or operator's switch has its starting circuit closed, and commences to test around its row terminals until it finds the row in which the selected trunk terminal is found, and then tests up that row until it reaches the trunk, where it stops, and remains connected to the trunk until finally released in one of three ways, viz., by the calling subscriber hanging up after the operator has answered, or by the operator clearing out manually by the sending machine at the conclusion of a cycle of impulses, whereby a complete connection is established. A very distinct advantage is gained by the use of two-motion switches for primary and secondary selectors, because there being ten rows of bank terminals of ten each, the entire one hundred may be tested in a maximum of twenty steps of the switch. The interrupters and sending machine are timed so as to deliver at the rate of about one thousand impulses per minute, with the battery voltage normal. Any drop in the battery which would affect the switches is compensated by a corresponding drop in speed of the sending machine. At the normal speed stated, however, a high number line in the calling group and a high number trunk in the corresponding group, can both be found and connected in less than one and a half seconds. Where the numbers are low, the action is practically instantaneous, and it is to be noted that the primary and secondary switches are operated simultaneously, that is to say the primary is testing for the line while the secondary is testing for the trunk.

FIG. 10.—Automanual operators desk with three key-sets. Ashtabula Harbor, Ohio

Each operator has three key-sets mounted on a suitable desk (Figs. 10 and 11), each having associated with it certain signals which guide the operator in the performance of her duties. The key-set in general appearance and arrangement is quite similar to the key board of an adding machine or typewriter (see Fig. 12), consisting of a number of strips of ten keys each (see Fig. 13), numbered from one to naught in each vertical row. One of the signals associated with these keys is a calling lamp, which is lighted automatically when the key-set becomes connected through the secondary switch to a first selector trunk already connected to a subscriber's line. Observing the signal, the operator asks the subscriber for the number wanted, and proceeds to depress the corresponding keys or buttons. She then presses a separate starting key, and groups of impulses, corresponding to the buttons depressed, will thereupon be transmitted as already stated. The wanted subscriber's bell is automatically rung at intervals until the call is answered, but in the meantime it is both unnecessary and undesirable to hold the operator and so the secondary switch is cut off automatically by the sending machine as soon as the ringing starts.

FIG. 11.—Operator's desk

In practice, duplicate sending machines are arranged as shown in Fig. 14, with gang switches enabling either to be thrown in or out in case of necessity. Each machine comprises a cam drum working ten pairs of number contacts, with separate controlling contacts and a commutator. On one side the commutator is grounded and on the other connected to all of the number spring sets, and the number cams are so located that in the rotation of the drum they make and break at points of zero potential on the commutator, thereby avoiding sparking at the selective terminals. The operator's key-set is normally disconnected from the sending machine, but is connected thereto when the starting button is pressed, by means of a switch which is thereafter stepped forward one step for each rotation of the drum, shifting the connections for one key strip to the next in proper sequence.

Fig. 12.—Key board closed and open

After the whole number of groups of impulses has been transmitted, the switch is restored and the secondary selector is released automatically.

There are a great many other features which I would like to mention here, but I believe this brief description will render the general operation of the system clear and enable the tables and curves which follow to be read understandingly. It is pointed out that from the moment the calling subscriber takes down his receiver until the calling lamp lights before the selected operator, that operator has no duty to perform nor is her attention distracted. If in the course of events there should be waiting calls, they do not appear before the operators until the latter are free to attend to them, which is an important point. The instant a signal appears, however, the operator being free disposes of that call. The minimum answering time in this system is practically zero. In handling a call, the operator has only the buttons to depress, and as shown in Fig. 13, these are especially designed to require as small an expenditure of energy as possible. The swinging bar engages the locking flanges on the different key stems, but the keys are raised by light coiled springs. It is unnecessary to release a key for correction as the depression of another key in the same strip releases the one previously set.

FIG. 13.—Key board buttons

FIG. 14.—Duplicate sending machines

The description of operation which I have given applies of course to trunking between exchanges as well as to connecting lines in the same exchange. The operation is no different, since the trunks between switches may extend any distance. Obviously only one set of operators is required, because all working impulses go forward though the first selector trunks, that is to say from the operator, through her trunk to the point where the call originated, and then forward through the talking trunks or links as they are built up. Thus, no talking trunk is brought into service or tied up until it is actually required, and moreover, since the subscribers automatically release when they hang up, no trunk is tied up an instant longer than is required.

Fig. 15 is a diagram showing the clearing-house connected to three exchange switching centers, *A*, *B*, *C*, directly connected by talking trunks *T T* shown in light lines, and all connected to the clearing-house by special or operators' trunks *O T* shown in heavy lines. At each of the exchange centers three subscribers' stations are shown connected to the primary selector switches *P S*, and the selective switches, *S S*. The operators' trunks have secondary selectors *O S*, containing in their banks terminals for the primary selector links. At the clearing-house the operators' trunks *O T* are arranged for automatic distribution among the operators' key sets in a manner similar to that shown in Fig. 3. It will be observed that the talking trunks *T T* between exchanges, which carry the traffic load, are absolutely independent of the operators' trunks, and have no relation whatever to the clearing-houes. The operators' trunks are worked at 100 per cent efficiency all the time, each being tied up for any call during a period of a few seconds only while the wanted connection is being established and being then free to take on another call and so on. The number of these trunks required to any switching center is proportional to the originating traffic therein, and would usually be less than one per cent of the number of lines terminating at that center. The course of a connection may be traced as follows:

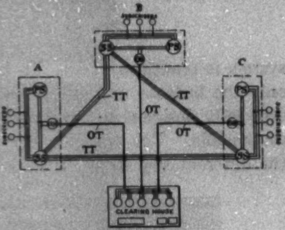

FIG. 15

Suppose a call to originate with the first subscribers' line in the exchange *A*. This is automatically connected to an idle primary selector switch, *P S*, thence through the link of that switch to an idle secondary selector switch *O S*, and an operators' trunk line *O T* to an idle key set at the clearing house. Thus the calling subscriber is confronted by the operator at the instant of his access to the first piece of apparatus, that is the primary selector in his own exchange, in the same manner that he would be confronted by a manual operator physically present in that exchange. The operator in this case having ascertained the number wanted, sets it up on her key set (Fig. 12), and presses the starting key. Impulses are then transmitted from the sending machine at the clearing-house, out over the operators' trunk, through the secondary selector at exchange *A*, to the first selector switches of the set *S S* which is permanently connected to the primary selector *P S* to which the calling subscriber is temporarily connected. The impulses corresponding to the first digit of the number cause the first selector switch *S S* to select a local connector or selector, or a trunk leading to the desired exchange, which we will assume in this case to be *B*. The trunk terminates there in a second selector switch *S S* and the impulses corresponding to the next digit cause this second selector to pick out either an idle connector containing the line wanted, or an idle third selector through which the connector can be found by a fourth set of impulses, depending on the size of the exchange *B*. As soon as the connection is completed, that is to say, as soon as one complete cycle or set of impulse groups have been transmitted from the sending machine, its connection with the operators' key set is automatically opened, and the secondary selector *O S* at the originating exchange, *A*, automatically drops off and disconnects the operators' trunk, being immediately thereafter available for another call. Thus, the operators' function having been fulfilled, in accordance with the rule hereinbefore stated, with the least expenditure of time or energy by the operator, she is instantly relieved, free to take another call, and the control of the connection through the talking trunks and switches remains entirely with the connected subscribers. When they hang up their receivers, all the switches are instantly cleared out, and ready for further use.

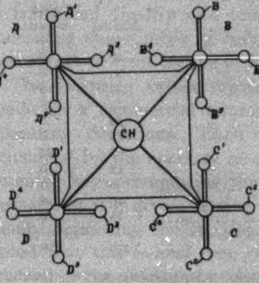

Fig. 16.

Fig. 16 shows the clearing-house principle applied to a subdivided system having four districts, *A B C D*, the first of which has sub-centers *A*1 *A*2 *A*3 *A*4, the second sub-centers *B*1 *B*2 *B*3 *B*4, and so on. The clearing-house *C H* is connected through operators' trunks *O T*, to the district centers and thence to the sub-centers, the method of handling calls being the same as that explained in connection with Fig. 15.

COMPARISONS OF SYSTEMS

In order to arrive at a true comparison of the actual labor required of the manual and the automanual operator in handling a call, the following analytical tables have been prepared, giving a unit energy value to each of the different movements required of each operator and assigning that value in accordance with the judgment of traffic experts.

TABLE OF COMPARATIVE WORK UNITS BASED ON NUMBER OF MOVEMENTS OF AN " A " OPERATOR IN HANDLING A LOCAL CALL

	Manual	Auto manual
1. Operator to note line signal	10	3
2. " insert answering plug	50	0
3. " " open key and say " number "	30	5
4. " " pick up calling plug	30	0
5. " " reach for and test multiple	75	0
6. " " insert calling plug	50	0
7. " " close key	25	0
8. " " set up number	0	25
9. " " ring called party	15	0
10. " " press starting button	0	5
11. " " observe disconnect signal	10	0
12. " " disconnect both cords	75	0
Total	370	38

EXTRA MOVEMENT OF " A " OPERATOR IN HANDLING A " B " CALL

	Manual	Auto manual
13. Operator to depress order wire button	15	0
14. " " ask for trunk assignment	30	0
15. " " depress branch exchange button	0	5
Total	45	5

MOVEMENT OF " B " OPERATOR IN HANDLING A CALL

	Manual	Auto manual
16. Receiving order for trunk and assigning same	15	0
17. Observing and assigning idle trunk	15	0
18. Pick up trunk assigned and reach for multiple	100	0
19. Test multiple jack	10	0
20. Insert plug in multiple jack	50	0
21. Ring called party	10	0
22. Observe disconnect signal	10	0
23. Take down trunk	50	0
Total	260	0
Grand total	675	43

It will be noted that in the handling of a purely local call the manual operator is represented in 370 work units as against

38 work units for the automanual operator while in the handling of a trunked call the manual operator is represented in 675 work units against 43 for the automanual operator.

In addition to the foregoing comparison of mental and muscular effort, it is possible to represent in foot-pounds the work done in lifting the plugs, cords, and weights, overcoming the friction of the cords against their associated plug seat walls. In one thousand completed connections and disconnections, about 2,917 ft-lb. of energy are expended by the manual operator, that are not required and are not expended in the corresponding work of the automanual operator. The manual operator may average 250 calls per hour, but the automanual operator easily handles 1000 calls per hour, so that a saving of 2,917 ft-lb. per hour must be credited to the automanual system. This is presented as evidence that my purpose of relieving the operator of all unnecessary work is fully accomplished. I believe this saving is translated directly into terms of higher efficiency, not only increasing the number of calls handled, but cutting down the percentage of error by the lack of strain on the operator.

The following tables represent three sets of service tests made on a commercial automanual switchboard under actual operating conditions. Each test represents the total time consumed by the operator in observing the call, depressing the listening key, pronouncing the word " number ", repeating the numeral as it is given, setting up the same on the key set, and finally depressing the starting key. It should be particularly noted that this is *total* time per operator call, and not merely answering time, which is what the manual companies usually give.

First 100 Records

Longest individual period	12.40	sec.
Average five longest individual period	7.44	"
" ten " " "	6.34	"
Shortest " "	1.60	"
" five " " "	1.92	"
" ten " " "	1.96	"
" entire 100 records " "	3.396	"
Hourly rate at which calls were being handled	1060	

Second 100 Records

Longest individual period	7.60	sec.
Average five longest individual period	5.52	"
" ten " " "	5.34	"
Shortest " "	2.00	"
" five shortest " "	2.04	"
" ten " " "	2.18	"
" entire 100 records " "	3.374	"
Hourly rate at which calls were being handled	1067	

Third 100 records

Longest individual period	5.40	"
Average five longest individual period	5.32	"
" ten " " "	4.44	"
Shortest " "	1.60	"
" five shortest " "	1.65	"
" ten " " "	1.80	"
" entire 100 records	3.16	"
Hourly rate at which calls were being handled	1139	

The first and second records were made by the same operator, and the third record by another, but neither of the operators knew that the record was being made.

These are not selected records but are all of the records made on the same day and all represent actual calls.

COMPARISON OF MANUAL AND AUTOMANUAL OPERATING FORCE

A comparison between a manual and an automanual operating force in handling a traffic load is shown in Fig. 17. This traffic load represents 4162 working lines connected with a main and a branch exchange located in a western city. About 21 per cent of all calls (flat rate) are trunked. The calls handled during the busy hour in both exchanges average about 185 per manual operator.

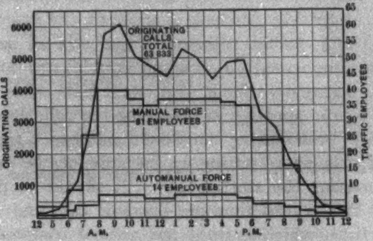

FIG. 17

THE MANUAL FORCE	THE AUTOMANUAL FORCE
2 chief operators	2 chief operators
1 information operator	1 relief operator
5 supervisors	11 operators
3 relief operators	—
50 operators.	
—	14 employes.
61 employes	

It will be noted that the manual " B " or trunk operators and the trunk calls are omitted from this chart. The automanual makes its greatest saving where branch exchanges are employed; the heavier the trunking, the greater the saving with automanual because it eliminates trunk operators. Notwithstanding that the chart deals only with " A " operators, a reduction in employes in favor of automanual amounting to 77 per cent is nevertheless effected.

COMPARATIVE COST IN HANDLING MANUAL TRAFFIC

No plan is known to me that has been utilized heretofore between manual operating companies in comparing their costs of handling traffic. The factors which seem to have precluded such comparison are:

1. Variation in salaries.
2. Variation in trunking percentages.
3. Variation in calling rate per line.

The only basis used for calculating traffic costs has been:

Cost of handling traffic per line.
Cost of handling traffic per station.
Cost of handling traffic per 1000 originating calls.

The first two cannot be considered as they are not based on volume of traffic handled. The third could be used for a system having a single exchange, but would be unfair to a system having more than one exchange because neither the trunk operators nor the traffic they handle is taken into consideration. Thus a system trunking 50 per cent of the calls handled would suffer in comparison to a system trunking only 25 per cent of calls handled.

The plan of equating calls has been used for comparing separately the equated calls per *A* operator hour and equated calls per *B* operator-hour in different systems, but no plan of equating both *A* and *B* calls to a standard unit has ever been used, to my knowledge.

COMPARATIVE MANUAL AND AUTOMANUAL OPERATING COSTS

Figs. 18 and 19 are compiled for the purpose of comparing costs in handling traffic, as between the manual and Clement automanual methods, regardless of variations in salaries, trunking percentages or calling rate per line. These tables are based on the rendition of a four second answering service in the manual systems and a three second service in the automanual system.

A standard unit is necessary by which every manual system may be measured and for this unit is employed the flat-rate non-trunked call as it appears in a common-battery multiple switchboard, and for convenience in comparison the cost of handling 1000 such calls is used as a basis.

Calls other than flat-rate, non-trunked calls require equalizing in accordance with the ratio of effort and time consumed, which is easily accomplished by the use of the multiplier given on the left margin of the curves shown in Fig. 18, as indicated by the point of intersection between the curves and the vertical line corresponding to the previously determined trunking percentage.

Having equalized the calls in accordance with the tables, then divide the total present daily operating expense by the number of such daily equated calls and place the decimal point to show the cost per thousand equated calls.

A comparison can then be made between the cost per thousand equated calls thus arrived at and the cost shown in curves of Fig. 19. At a first glance the multiplier of 95 for incoming trunk calls appears to be rather high but this is explained by the unavoidable loss in efficiency of a trunking operator during evening and night hours.

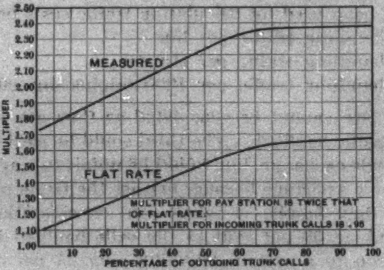

FIG. 18

A hypothetical example of a telephone system having two exchanges, shows equated calls for the following daily traffic.

Main	Exchange	130,000	flat rate calls, 5 per cent trunked	148,200
"	"	3,000	pay station calls, 5 per cent trunked	6,840
"	"	6,500	incoming trunk calls	6,175
Branch	"	12,000	flat rate calls 50 per cent trunked	18,000
"	"	200	pay station calls 50 per cent trunked	600
"	"	800	measured calls, 50 per cent trunked	1,800
"	"	6,650	incoming trunk calls	6,317
			Total equated calls	187,932

Fig. 20 shows an automanual schedule applied to the branch exchange of the western telephone company previously referred to and proves out the automanual cost curve in Fig. 19. It will be noted in Fig. 20 that the cost per thousand calls on the automanual operators' schedule is 19.5 cents. By referring to the cost curve in Fig. 19 it will be observed that the cost per thousand automanual calls is 19.5 cents where the average operators' salary is $25.00.

The clearing-house principle illustrated in Fig. 15 is applicable to existing systems, with practically no rebuilding except that of the central office switching equipments; the subscribers' instruments and lines, as well as the general method of handling the subscribers, remaining unchanged. The particular feature which renders this possible is the automatic secondary distribution, which brings calls to the operators at one or more centers without the necessity of massing or concentrating talking trunks. This feature is peculiar to the automanual systems, and the economies flowing from its employment may be best illustrated by presenting an extreme case involving the handling of the entire traffic load in a large city, at present divided between two competing systems both equipped with manual switchboards. The two systems may be designated as *A* and *B*, and the following tables are based on an actual study of their traffic conditions in detail. Table 1 shows the number of telephones in operation in each system, the approximate traffic handled by both companies, and the cost of handling the traffic. Table 2 shows the estimated increase in traffic of both companies as well as the additional cost of operating, if manual trunk lines were connected between two systems, permitting a general interchange of

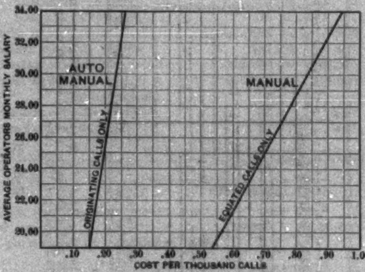

FIG. 19

calls. Table 3 shows the cost of handling the combined traffic by automanual clearing-house methods exclusively.

The automanual service is uniform and accurate, because the switching apparatus is all operated over local central office circuits of uniform and known resistance, by expert operators under proper discipline. The benefits of the manual method of operating are preserved, but no cords or plugs are employed, and the service is secret because the operators are cut off automatically when connections are established, and have no way of cutting in on any connection thereafter. The distribution of

A.M.								P.M.												NO. OF OPRS.	REMARKS
12-5	5-6	6-7	7-8	8-9	9-10	10-12	11-12	12-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-12	11-12		
							AUTOMANUAL OPERATORS SCHEDULE														
1	1	1	1														1	1	1	1	
		1	1	1	1	1		1	1	1	1									2	
		2	2	2	2	2		2	2	2	2	2								1	
			1	1	1	1	1	1		1	1	1	1							1	
				1	1	1	1		1	1	1	1	1							1	
				1	1	1	1	1		1	1	1	1	1						1	
				1	1	1	1						1	1	1	1				1	
							1	1	1			1	1	1	1					1	
							1	1	1				1	1	1	1				1	
								1	1	1	1	1		1	1	1	1			1	
																				1	DAY CHIEF
																				1	EVE. "
																				1	RELIEF OPR.
5	1	2-4	4	7	7	7	6	6	7	7	7	7	6	4	4	3	2	1	1	14	NUMBER OPERATORS
506	232	1027	2845	5870	5974	5061	4723	4489	5271	4598	4228	4929	4431	2606	2806	1628	816	314	238	63 833	ORIGINATING CALLS
506	238	342	711	838	857	723	787	723	753	657	603	704	822	826	701	541	408	314	238	871	CALLS PER OPR.

Number of lines working, 4162; calls per line, 15.5; 14 operators at $25.00 per month, $350.00; 63,833 originating calls × 28 days (26 week days and 4 Sundays) = 1,787,324; monthly originating calls ÷ into total monthly operating expense, $350.00; =19.5 cents per 1000 calls.

FIG. 20

calls among the operators is uniform, and this condition prevails at all times without regard to the number on duty. Each operator's position has a jack containing contacts for the telephone plug and associated contacts for the secondary control circuit of each key set at the position, these being opened when the operator pulls out her plug, so that calls come only to those positions at which operators are actually present and ready to handle them. All other positions are dead, and the calls come to the live positions in rotation. An operator may take calls at any position, by simply plugging in there and light loads can thus be handled at a single position. Patrolling of the switchboard is avoided, and as the number of operators can be varied in direct proportion to the load, no one operator is busier than an other at any time.

TABLE I.—PRESENT CONDITION

	System A	System B	Total or Av.
Number of subscribers' lines	18,666	13,219	31,885
" " " telephones	42,000	27,000	69,000
Percentage of telephones to lines	2.25	2.05	2.16
" " business telephones	54	51.5	53
Employes traffic department	498	320	818
" average monthly salary	$32.50	$31.50	$ 32.11
Monthly operating expense	$16,185	$10,080	$26,265
Originating calls daily	294,000	216,000	510,000
" " " per telephone	7	8	15
Percentage originating calls trunked	57	24	43
Cost per thousand originating calls	$1.97	$1.67	$1.84

TABLE 2.—INTERCONNECTION

Increase in calls per telephone	1.9	3.1	2.4
Calls to other company	79,800	83,700	163,500
Increase in percentage of originating calls trunked	9	21.2	14
Additional employees	153	168	321
Increased monthly operating expense	$5,184	$5,292	$10,476
Increase in cost per thousand calls	0.27	0.13	12
Percentage of increase in pay-roll	32 per cent	52 per cent	40 per cent

TABLE 3.—AUTOMANUAL

The cost of handling the combined traffic of both systems amounting to 673,500 originating calls per day with the Automanual-clearing-house system based on an average operator's monthly salary of $32.00 would amount to twenty five cents (0.25) per thousand calls, on a monthly operating expense of $5,051.25. *This makes a reduction in the present operating expense of 86 per cent.*

The operator cannot show favoritism, as without special provision she cannot know who originates a particular call, and any subscriber's call may be answered by any operator in the exchange. There is also a decided economy in the matter of space, the size of the operating room being considerably reduced. As regard material for operators, which is a consideration of moment in some parts of the country, it is pointed out that any person who can hear numbers and touch keys is capable of handling traffic automanually. This includes the blind, who make very efficient operators, not only handling the number keys dextrously with little practice, but also reading the lamp signals by touch. I have provided a special signal for the blind, however, so that for them lamps are unnecessary, and may be relegated to the monitors, unless they too are blind.

As the detailed circuits are not described herein, I will state that the talking circuit between subscribers when connected, is perfectly clear and in fact identical with the standard bridged common battery circuit employed in modern manual exchanges.

In closing, I wish to acknowledge my indebtedness to Mr. John P. Boylan, of Cleveland, Ohio, for his assistance in compiling traffic data for use in the preparation of this paper.

DISCUSSION ON "NEW AUTOMATIC TELEPHONE EQUIPMENT," AND "THE SEMI-AUTOMATIC METHOD OF HANDLING TELEPHONE TRAFFIC," LOS ANGELES, CAL., APRIL 26, 1911.

J. W. Gilkyson: Being responsible for the revenue produced by the manual system of this town, I hardly think it is incumbent upon me to discuss, or at least in any way to malign the competitor of the automatic. It has many phases which meet the requirements of the community. I hope, though, that in the future the semi-automatic will be the neutral factor in bringing together both the manual and the automatic. and I cannot help but think that will be the final result. The fundamental thing is economy—economy in central office operation, economy in central office equipment costs, the elimination of sub-exchanges, and the facilitation of the trunking appliances.

Mr. Keller: Regarding the automatic and manual service, I will quote from a letter I received from Europe from a friend of mine, who went to Berlin, Germany, to promote and build an automatic system. There are a few passages that are exceedingly interesting. Before going to Germany, he came to Los Angeles to see what we had, he returned by way of San Francisco. There he says, he changed his mind somewhat on one phase of the automatic feature, namely, the secondary line switch. In our automatic system here, each subscriber has one individual line switch, and we use secondary line switches to a very limited extent—not at all in connection with the subscriber's line. But in San Francisco, each subscriber has one individual line switch, and before the individual line switch reaches a first selector switch, it passes through a secondary line switch which reduces the number of first selectors to a minimum.

Mr. Luberg has always been opposed to this, but he says since looking into it very carefully in San Francisco, he has changed his mind and he finds the secondary line switch is working very satisfactorily. If he is right, I am inclined to believe it will do a great deal towards simplifying the apparatus in general use.

He says further that at Hamburg he saw in operation there a 40,000-line central exchange under one roof and it is now being enlarged to 80,000 lines. He states that it is a manual distributing system, which means that the call comes in at an A board where one A operator is provided for 800 subscribers. This operator has nothing to do but to extend the call to a B operator who answers the call. The B operator again extends the call to a C operator in the wanted 10,000 group. C has the multiple. After extending the call the B operator is cut out of the connection. The service is supposed to be fine. Referring to the cable service he mentions here that it is frightful. He says the average cable length for a subscriber is three and one-half miles.

Further on in his letter he asks what our average is. I have not quite arrived at my figures yet, but in our Olive Street exchange we find it is about a mile.

"Just now," he writes "we are installing a half-automatic exchange in Amsterdam. By the term 'half automatic' we mean a system similar to the Clement Automanual, *i.e.*, the subscribers station is the usual C. B. manual apparatus. When the subscriber calls he gets a connection first with an operator who sets up the connection with a push button keyboard. After the impulse machine has run down, the operator cuts off again. The switches are absolutely identical with the regular automatic outfit."

He says that the engineers of the German government, for as you all know, the postal authorities handle the telephone situation throughout Germany, deliberately put in this half automatic system with the intention of putting in a full automatic later on. He says the only reason that they do not make this change now is because of the cost of the calling device which is estimated at about five dollars more than the ordinary telephone instrument. Otherwise, they would make the entire installation automatic at present. Whenever they want to change their apparatus to automatic they can do so.

That looks to me like a very sensible method. If they must have a full automatic they can do so without any extra expense in the installation—that is without any waste.

It seems that the government engineers have decided that measured service should be furnished where a manual exchange is in use, and a flat rate with automatic. They take the stand that it does not cost materially more for a man to have many calls over an automatic phone than it does for a limited number of calls, while with a manual board the expense of operating increases in proportion to the number of calls, which we all know to be a fact.

"A Dr. Steidle, in Munchen, has designed what he calls 'automatic group systems.' About twenty to forty subscribers with very few calls per day (metered service) say about two to three calls per day, are connected to a relay switching station located in the basement or attic of the house, or placed in the near neighborhood. The relay combination gives access to one of the two exchange lines. In the exchange the calls are handled manually at present. Calls to the group line are distributed by 40 point connectors, also placed in the relay groups. He figures for a 20,000-line plant about 6000 heavy talkers with individual lines, and 1000 relay groups with an average of 14 lines attached to each. He therefore would provide 1000 relay groups with 1000 batteries. Now, don't smile at that, they actually put in about 60 of such groups, in and around Munchen.

"So you see we Germans just at present have the two telephonic extremes—an 80,000 line single exchange and a thousand fold subdivided plant seriously proposed by a very fine telephone engineer."

I should not wonder if we may have a similar situation to face sooner or later. Personally, I cannot say anything about half automatic, for several reasons. In the first place, I don't know much about it, but it seems to me that if the half automatic is used as a step forward toward a full automatic, that it is the proper step to take, but it also looks to me that if one cannot change it to a full automatic it is a step only half forward. It is just like changing from a horse car to a cable car—a sort of step between. Now, if that step between is a step toward making it a full automatic, I think it is a step in the right direction. I think that the full automatic will soon be the only factor in the field.

K. B. Miller: The idea suggested by Mr. Keller of using the semi-automatic as a stepping stone to the full automatic is one way of looking at it. The probabilities are that the one controlling factor in the matter, a factor which is likely to be more and more a controlling influence, is the atititude of the public. The fact is that the telephone companies are serving the public and it is the public that must be pleased. Now, my experience so far, has shown me that either the automatic, where the subscriber spells out his own connection with his finger, or the manual, where the subscriber merely asks for what he wants, is capable of giving good service, and either of them is capable of satisfying the public.

It is often argued that the automatic's success in pleasing the public is transitory—akin to the liking of a child for a new toy. I have studied that phase very carefully and, while I know that some of you will disagree, I can only arrive at the conclusion that, at present, the public will be satisfied with either way of doing it, provided good service results, and we all know that good service may result from either method. The atititude of the people may eventually swing one way or the other or it may split and result in two permanently disagreeing factions. There seems to be nothing impractical in the idea of the combinationof the two schemes, giving automatic instruments to those subscribers who want them, and connecting these directly with automatic switches; and giving to those subscribers who want to feel an operator at the other end of the line, no automatic transmitting devices, but merely ordinary telephone instruments, practically along the lines of Mr. Clement's system. The same automatic switchboard would make all the connections and disconnections, these being controlled directly by the subscribers in the one case and by the operators in the other.

A. H. Griswold: I was very much interested in Mr. Winston's last paragraph, which is one of the strongest in his paper.

"The man who attempts to prophecy what the future equipment will be, is putting himself up very much as a prophet."

In comparison with many of the other sciences, we have had rapid changes of type of telephonic equipment, and certainly we will have in the future a great many more changes before we approach the ideal.

In the final analysis, the primary thing that we must strive for is service that is reliable and efficient, and therefore service that the public desires. It may not be possible to combine in one system a type of service that will meet the desires of all of the people. There may be room for two classes of service, just as there is for the electric car and the steam car, one may offer advantages that the other does not. The thing, therefore, that must be studied is what the public wants. It may not be determined by engineers particularly, any more than to establish these various systems and try them out. It may not necessarily mean the most beautiful piece of mechanism, or the most rapid service, but it will mean the most reliable and most efficient service.

Most of us in using the telephone, if the service be reasonably reliable and the speed of answer be reasonably fast, do not worry very much about the time interval.

The proper equipment in the future may be manual, full automatic, the so-called semi-automatic, semi-manual, automatic distributing system, or some other type, but what ever it is we must have the first considerations fulfilled, that it must give reliable and efficient service, and service that the public desires. Having these first requirements, the secondary consideration, and one which I sometimes think we let precede the first, is the question of providing the best type of equipment at the least ultimate cost, meaning not only initial cost but resultant and subsequent charges.

It might be interesting to know if Mr. Winston in his automatic distributing system has made any provision for reverting calls. That is, when one subscriber calls another subscriber on the same line.

K. B. Miller: In connection with the reverting call proposition, I agree that we ought to hear from both these gentltmen about it. The reverting call is a pretty mean thing to handle with the manual system, as we all know. It seemed at first wholly impossible for an automatic system to take care of it, and yet automatic systems have been made to do this in an even more direct way than the manual.

A. H. Babcock: The automatic and the semi-automatic telephone systems appeal to me from the standpoint of the man who pulls the switch at the subscriber's end. In other words my mind at present is concerned entirely with the subscriber and not with the engineer who is constructing these things. I have a feeling after seeing the inside of one purely automatic telephone system, and having had it very fully explained by the engineer who installed it, that if there is a failure on my part to receive connection with the number that I want, it is due to my failure in handling the apparatus, rather than to the failure of the apparatus itself. Consequently, when I am asked to use a telephone system wherein I give an operator the number that I want, and she does then that which I would do, which is, I understand, the semi-automatic system, it is merely introducing another link and a very weak link into that chain.

I call a number in San Francisco very frequently. Five, six or seven repetitions of that number have been made repeatedly, and they are spoken distinctly into the telephone, too. I can't see from the subscriber's standpoint what there is to be gained by putting that extra link into the chain. I prefer a piece of mechanism handled by myself, rather than the intervention of an operator who may be tired, may not be well, may be thinking of other things—the human element, entering in all the time between what I want and what I get. In other words, the nearer we get in all our public service work, to a piece of apparatus directed by one person, the nearer we will come to getting satisfaction. Now, remember, I am speaking merely from the subscriber's and not from the engineer's point of view.

Ralph W. Pope: I wish to call attention to one of the features of the manual system, which is the only system used in New York City, that does not appear to have been considered in these discussions. I refer to the distinction between the individual subscriber working direct with the central exchange, and the subscriber working through a private branch exchange. I understand that in New York City the growth of the private branch exchanges has been very large, and where the service is sufficient to warrant it, is always preferred. I have had both experiences. Formerly, until four years ago, we worked direct with the central exchange. For the last four years, we have worked through a private branch exchange. The service through the private branch exchange is far more satisfactory, for the reason that the operator is more in sympathy with the business, pays more attention to the calls, and is apparently not overworked. That is to say in our particular exchange there always appears to be a little margin of leisure, so that the number can be repeated back, and the operator will not get away from the instrument before the subscriber has an opportunity to correct the number if wrong. When the number is repeated back direct from the exchange, half the time I can't understand what it is, and if I do and it is wrong, the operator is gone before I can make the correction. That is not true of the private branch exchange. This leads me to corroborate Mr. Gregory's statement that what we want is not so much rapidity of service, as reliability of service. There is loss of time, no doubt, in handling a call through a private branch exchange, but then there is also a gain in comfort. In working with the central exchange, we are expected to keep the telephone to the ear until the final connection is made. With the private exchange, the number is given and the telephone hung up and when the connection is made the operator rings up and we go ahead with the work. In other words, we don't have to wait with the telephone at the ear while the connection is being made. That is to me a very satisfactory arrangement, through the elimination of being obliged to sit and wait for what may be a quarter of a minute or half a minute or a minute, with the telephone at the ear. I may say right here that while I do not use the central office connection regularly, sometimes when I am in other parts of the city where I have to call up the central office and do this waiting, it is especially annoying. This all tends to bring in another feature in the telephone service, and that is the comfort of the subscriber. Mr. Babcock admits that he gets irritated. Subscribers wish to eliminate all the trouble possible, and one of the principal virtues of the common battery system is that it has eliminated the necessity of turning the crank. We simply go through the motion of taking up the telephone and putting it to the ear, and then if you simply hang it up and wait until your bell rings, you know that you have your connection.

J. W. Gilkyson: I wonder if a comparison has ever been drawn by Mr. Babcock with reference to the number of mishaps that he might have with the automatic in placing a call himself. He does not charge that error up to himself. He simply hangs up and tries it over again. He may do it two or three times, while he immediately becomes provoked at the manual operator that mistakes his number.

With reference to the private branch exchange, that is a question that we have had considerable difficulty in handling. In many instances, operators are employed by the parties served with the private branch exchange service; many of the young ladies receive a box of candy, etc., from certain individuals of the corporation and get excellent service from the company. On the other hand, the man that is abrupt, gets poor service. I believe if the standard of the private branch exchange could be adopted by the company that there would be a more uniform service. I don't think Mr. Pope's would be better or worse. That is a condition that exists. He speaks about placing his call with the operator. She performs that function that ordinarily a man on a direct connecting line would have to withstand. If that line is busy at the time he calls, he is told the line is busy. The operator has performed that function, and he has to wait. Where would the private branch exchange differ if he gets the report that it is busy? If the private exchange gets a report that it is busy, she makes a note and calls it at another time, and the connection is put up, and the man who is busy, figures it out as an excellent service, but he does not perform the function himself. It is the duty of the girl that operates the private branch exchange, which, of course, could not be expected in service given to the public, and could not be taken into consideration.

A. H. Babcock: I yield to no man in my respect the telephone operator as a woman earning her own living. I find no fault with the operators, because I know of some of the conditions under which they work. I have a great respect for their astounding skill by which they handle an immense number of calls per hour. But I do find serious fault with the condition that produces the situation I have just outlined. My conversations referred to are with a private exchange operator who is on our own payroll. I hear her struggling with the central office to get that number straight, and when I say that the number called for has been twisted out of shape six or seven times, it is by skilled operators whose business it is to handle those calls—not between me and the operator, because our private exchange operator knows perfectly well what number I want. It is not my grief, except as I have to wait, but it is hers. It seems to me the farther we can get away from that kind of thing, the better. I don't think it is fair for Mr. Pope to compare his present easy time, pushing off his job of making a telephone call onto his paid operator, with the troubles a subscriber has who cannot afford, by reason of his small service, to hire and pay a private exchange operator. The condition to be met is to give good service to the greatest number—not to a few of us who have private exchanges, or who can send boxes of candy to the operator. Possibly if the telephone expert who has just made the suggestion that a box of candy would improve the service, had realized the implication contained in that suggestion he would have expressed his thought differently. A Public Service that requires lubrication by means of boxes of candy needs some intelligent reconstruction.

F. C. Newell Jr.: Mr. Babcock has just stated that the public is really the supreme court in this case. In cities like Chicago and New York, where there is a great foreign population, the numerals are a sort of universal language. When the operator cannot understand the foreign tongue, it seems to me the numerals are to be preferred. I would like to have somebody state the advantages and disadvantages of the foreign population.

K. B. Miller: In France, I am informed by some of the foremost French telephone engineers, they consider that very point as one of the strongest arguments for the automatic. It seems that the French language, with which I am not familiar, does not lend itself as readily to the spelling out of the digits of a number as our language does, and that as a result there are a great many more misconnections, and a great slowing down of the service. That appears particularly in the trunk operations where an A operator passes a connection on to a B operator. The difference between the number of calls that a B operator can handle in France with the same type of equipment, and that which we handle in this country in manual exchanges, is remarkable, and I have heard it attributed mainly to that fact that the French language does not lend itself so readily to the transmission of numerals. Undoubtedly other factors enter also.

A. H. Babcock: How about the Chinese exchanges? Is there anybody from San Francisco who can give the experience with them?

Mr. Keller: The Chinese in this city have a private exchange of their own, or, rather a small exchange with a Chinese operator, who speaks English and establishes the connection for the Chinese. They have not yet adopted the automatic in this city. In San Francisco, however, they have adopted the automatic system, the automatic calling device with Chinese numerals on it instead of the numerals we use, and operating exceedingly successfully. In fact, it has been more generally accepted by the Chinese in San Francisco than by the general public so far.

There is another feature that I have just been told of by a young man that came from Havana. In Hanava there are a great many languages spoken, and the automatic there has become very popular on account of the fact that all of the various nationalities can secure their parties without having to converse with any operator or any other person except the party they are calling.

Ralph Bennett: I am very much interested in the four-party line. We have one at our residence from the old company, and I have discovered that I hear not only our own but all the neighbors calls from both sides of the line.

Very frequently they ring on our line, one bell, and after ringing awhile we answer. "Central wants the party whose ring is two bells," When told so she says. "Oh, I didn't know that. They didn't tell me that." It seems to me that this difficulty can be readily corrected on an automatic where the subscriber rings the correct call automatically.

K. B. Miller: It is a simple matter to have selective ringing on party lines in manual systems. Several successful schemes are available.

W. D. Moore: We maintain in our system what we call an observation desk. It means that the service we give is constantly under observation. This observation desk indicates the moment the calling subscriber takes the receiver down; the moment the operator plugs in to answer; the moment she rings; the moment the called for subscriber takes the receiver down to answer; the moment he hangs up; the moment the disconnection is made. This action is automatic—we do have a little automatic—and different colored lamps indicate the different movements and it is recorded as the action takes place. Now in each exchange there are so many observations taken each day. That is the way we determine the standard of service that we are furnishing. It also indicates the efficiency of our operating force. We figure that any operator—that is, the answering operator—can handle, during the busy hour of the day, the peak of the load, approximately 265 calls. That is, she can finish 265 calls. Now if we find there is a falldown in the service in any particular exchange, by referring to the peg count, which is taken on the tenth day of each month, we note that the operator has become loaded down and a redistribution of lines is made throughout the entire number of operators and the result is, of course, a natural improvement of service. We also have certain methods by which we procure increased efficiency from the operating force. Of course this is all worked out upon what our experience has shown us that one operator can handle without an excessive strain.

Our figures showed for this city—the last time I heard them quoted, which was some six months ago—that there was one-tenth of one per cent of the entire number of completed connections that were rung in error and this is a very small fraction of the total number of calls.

That is taken from the observation service. We can tell at any period of the day, any hour, just what class of service we are giving in a particular exchange, in a particular town or territory; and the figures have shown that one-tenth of one per cent of all the calls completed were rung in error. So, as to that part of the manual system, some particular fault of the automatic can also be found to offset it.

It appears to me, taking the subject as a whole that it is as Mr. Griswold said when he referred to the last paragraph of Mr. Winston's paper that he sums up the entire proposition in a few words. He said that it is probable that before many years the differences of opinion which now exist as to the relative advantages of manual and automatic will disappear, and that definite standards will be adopted for the various conditions of practice. There is no question about that. I believe all telephone engineers agree that we can predict that without fear of being contradicted.

Mr. Clement described his semi-automatic system, but as I have not read his paper through, I could not grasp the full details, but I believe, just speaking for myself personally, that this is the eventual outcome. I might also refer to a remark of Mr. Keller He said that the semi-automatic would be, or could be used as a stepping stone to the full automatic and that if that could be done, it would be very desirable. I believe that what he was thinking of was the saving that could be made by deferring the expenditure necessary for substation equipment to some future period. It is my opinion that is not what is going to happen in the future. I think that the automatic will be the stepping stone to the semi-automatic for this reason—you know that recently there have been certain laws enacted which prohibit the employment of female labor for more than eight hours out of any twenty-four. This places a burden on the smaller towns and exchanges. In a large city where there are some very busy people, such as railroads and other large offices, using the telephone constantly, the amount of work that the subscriber must do to secure his connection is an important factor, whereas in a smaller town it need not be given consideration, as there are no large business houses using the telephone at a very rapid rate. Therefore it appears to me that the automatic will ultimately be used for furnishing service in smaller towns, say up to a capacity of 1,000 lines, as the part the subscriber may play in procuring his own service is not very important. In the larger cities where a man has his mind occupied with various details, he is not so anxious to manipulate the instrument himself. As a result, it appears that ultimately the desirable service, or the service the public is going to demand, would be the manual.

In handling the manual service, our present switchboards are designed so that we can place within the reach of one operator 9,600 lines. Of course, on a jack per line basis, this would mean an additional number of stations probably a ratio of 70 lines to each 100 stations, but when you reach the capacity of 9,600 lines, it means additional multiples. It means that you will have to install trunk switchboards that will have additional multiples and are considered second units. The capacity of each unit will be 9,600 lines. That is, an operator answering a call on the first unit must out-trunk same to the second unit.

Now in a city like New York, where they have over 300,000 telephones, it resolves itself to a question of what per cent of the total calls are out-trunked, and it is figured that when approximately 70 or 75 per cent of the calls are out-trunked, it is just as economical to out-trunk 100 per cent, which means all calls originating at the 'A' position will be out-trunked.

Mr. Clement describes a clearing-house system and also operating centers, but I could not quite grasp his idea. It would seem to me that the ultimate solution of this problem would be something like this—to provide a number of operating centers in a city like New York, each located at what we term 'Wire Centers', that is a particular center at which the greatest number of wires radiating from same would be the shortest, when you take down your receiver, your signal would show before the 'A' operator and after giving your call—say for instance Broadway 4519—she would then simply manipulate the keyboard and the rest of the action would be automatic, that is, it would select a trunk, arrive at the other office, select the particular number you wished to talk to and ring same—then you would have solved the operating problem and also the telephone problem as well as it can be solved in our day and time. I am of the firm opinion that the ultimate solution of the problem of handling telephone traffic in the larger cities is the semi-automatic method and that the full automatic will serve the smaller cities.

Mr. Schuler: There is one thing that the gentleman spoke of that interests all of us who are in the telephone business. We are in the telephone business for one thing, and that is to sell service. Now, the point in my mind is this, that the company that is in the telephone business and is going to do the most business is the one that sells the best service. I have in mind a place where the Bell Company had nine hundred subscribers and the Independent started with 250 subscribers four years ago. Now the Independent company has 1,567 subscribers and the Bell Company has less than 200. The one thing that accomplished it was service.

Now, what constitutes service. Service is constituted by a man going to his telephone and getting the number he wants in the quickest possible time and getting the best possible transmission after he gets his number. That is telephone service. If you go to your telephone and try and try to get a number and don't get it, and even after you do get your number you don't get transmission, you are not getting what you pay for, and the man in the telephone business is not delivering what he is paid for doing. In my mind the best proposition for delivering telephone service, I don't care whether it is wireless or with wires, or whether with telephone or without telephone, that will put A in communication with B and give A that communication in the least possible time and give them both the best possible transmission.

I have made a number of tests—I happened to be manager of the first two-wire system put in existence—I made a particular investigation of why we could not get business. The Bell people were not giving service. We were giving service so far as our calling and our transmission were concerned, but we were not giving service because the people did not use the apparatus right. Now, if we had had in that little Illinois town the automatic, or semi-automatic service, I believe we would have gotten the business. I called on 100 of our subscribers and asked each one which they thought best, which they preferred to use, and they preferred to use the manual service, but they admitted they could get better service over our lines, but they did not want to be bothered with the necessary trouble.

I have made a number of other tests in regard to service. I tried getting 100 subscribers on the manual and getting 100 subscribers on the automatic service. The automatic service was a new plant and everything was working right, and I would get my 100 subscribers in a great deal less time, making allowance for the parties who did not answer, the moments lost in waiting for parties who did not answer on one was as much as the other—I would get my automatic subscribers in less than 80 per cent of the time it took on the manual. I visited 100 subscribers and asked them which they preferred to use—whether they preferred to give the operator the number and let the operator call it, or the automatic. A large per cent preferred to give the number to the operator, so I am thoroughly convinced that the semi-automatic is the best equipment.

H. B. Tupper: Mr. Clement in his paper says, "It appears that after the operator has answered the calling subscriber and puts up his connection, she clears out and if the subscriber does not get the called party he has no means of determining whether that subscriber does not answer or whether that line is in trouble, unless he should flash his hook and probably come in on the apparatus again and go through the same sequence as the first time"

We use a method in the manual system, we have toll switching positions, automatic stick down keys, which work the same as those Mr. Clement speaks of. The operator plugs in to the subscriber's calling jack and the ringing is done automatically through a machine ringing segment on the ringing machine. This machine ringing device throws out alternating currents and direct currents at intervals on the operator's line to the subscriber, and it will continue to ring until the subscriber removes his telephone from the hook, which indicates he does not get it and he can get her again and tell her conclusively whether the line is in trouble or whether the subscriber does not answer. That is a point that should be embodied in the automatic—the possibility of the subscriber getting in touch with the operator without going through the sequence of working up his automatic machinery again.

C. L. Cory: I have enjoyed the discussion of the automatic, the manually operated and what has here been called by different names, the half or semi-automatic or automanual telephone systems. Considering the matter somewhat carefully from yesterday, it would seem that we should view the telephone situation fairly and from two entirely different standpoints, one with the attitude of the subscriber or customer, the other as necessarily viewed by telephone engineers who have been engaged for years in perfecting all of the very complex apparatus adopted and so successfully used in telephone systems.

The requirements of the subscriber may be compared to that of the customer requiring illumination, using electric light. Illumination from such a source of light is needed as a substitute during certain hours of each 24-hour day in place of the natural and free illumination available in day time. As long as the sun provides sufficient light the individual only finds it necessary to raise the shade to the window in his room. In the absence of sunlight many years ago man found it necessary to devise a substitute, and perhaps in the order of use, pitch pine, the candle, and the coal oil lamp, all of which sources of light were under the complete control of the individual desiring the service.

Upon the introduction of gas and incandescent lamps the service was not completely under the control of the customer. In somewhat the same way we may consider telephone service.

I myself frankly believe that the method by which one calls or attempts to get in communication with the person with whom a conversation is desired should be considered from the psychological as well as from the engineering standpoint, although of course the methods that may be employed by the customer and devised by the telephone engineer are engineering problems, but it will not do to lose sight of the attitude of mind of the subscriber in coming to a definite conclusion as to the best system which may be employed.

Those requiring the use of electric light had nothing to do with the change from the carbon to the tungsten incandescent lamp. Yet the service is much better and cheaper with the latter than with the former. Viewed exclusively from the standpoint of the customer, he might have been thoroughly satisfied for all time with the old carbon lamp, but nevertheless the customer is pleased and gratified as a result of the introduction of the tungsten lamp as a substitute for what was previously considered entirely satisfactory, namely, the carbon filament lamp. The illustration may be crude, but it may serve as evidence that the character of service planned for the customer by the inventor may not be the most desirable to the individual paying for the service.

Again suppose it is my desire to speak to Mr. Miller. As we are now both in this room I merely address him. The entire conversation is within our control; barring some noise or similar interference from the outside our mutual understanding of one another can not be prevented. Mr. Miller hears me addressing him and replies directly. Nobody can interrupt our conversation. In a way such a conversation may be likened to sunlight as a source of illumination. It is free. It is controlled as we choose and no interference is possible from others.

When artificial illuminants were introduced without question the idea was in so far as possible to get results approximating the illumination of the sunlight, not free of course, as this would be impossible. Similarly I can not talk with Mr. Miller when he is in Pasadena as I do here, nor can I talk with him when in San Francisco. We need some artificial arrangement, which is the telephone, in order to make our conversation possible at the greater distance. Notwithstanding this, my attitude of mind as I desire to talk with Mr. Miller when he is distant certainly approximates the condition which we can so readily establish here when we are within a few feet of one another. This obvious fact will certainly be admitted by all. It is the work of the telephone engineer to approximate that condition.

To put it in a little different way, Mr. Miller may be across the street, or in Pasadena, or Long Beach or Redondo or San Francisco, and I desire to talk with him. No matter where he may be it is my desire if possible to carry on a conversation with him as I may do here in this room. This is the attitude of every telephone subscriber. In order, however, to get into communication with Mr. Miller, what is my preference. Spell out his location myself, because that is what it amounts to in the automatic system, or remembering that I am subject to error, would I prefer to take the telephone off the hook, addressing an operator in the central office and trust to the system, which includes operators and devices, to connect me with him, no matter where he may be. I have been impressed greatly and much admire the mechanisms that have been evolved in the automatic system, but the question finally comes down to this: would I prefer to simply express my desire to talk with Mr. Miller by giving his number to the central, or individually spell out Mr. Miller's location myself so that I may talk with him.

The preference of the subscriber in such an instance, it seems to me, depends entirely upon conditions. It may be necessary and really demanded that the automatic system be used, by which every individual, no matter what language he may speak, finds it possible to spell out the location of the person to whom he desires to talk, as was stated here might happen in Havana, or any other city containing in its population subscribers speaking many different languages who use the telephone, but it does not necessarily follow that this is desirable in a city using say 300,000 telephones and covering an area less than the city of Los Angeles.

Naturally the telephone engineer has confronting him the problem of providing as far as possible a system so that I may talk to Mr. Miller if he is in Los Angeles, only across the street, or in San Bernardino or San Francisco in a manner as nearly as may be as we talk together in this room. As a matter of fact, I may not know in the beginning where Mr. Miller is, and it does seem that the plan where we have combined local and long distance service, whereby a skilled operator is used in locating the person to whom one desires to talk, may perhaps be much better than to have such locating done by the customer, who can not possibly be so skilled as a regular operator.

If the automanual as has been described in one of the papers here will make it possible for the subscriber to call up central, give the number desired, and then the operator in the central office by using a similar automatic device can the more accurately, speedily and economically connect the subscriber with the individual called, that system it would seem would be the best of the three under discussion as treated in the papers presented.

In conclusion it should be said, I think, that the problem of devising the best possible telephone system should be viewed not solely from the standpoint of the subscriber, but very largely so. At the same time, all of the possibilities should be given the most careful consideration by the telephone engineer. The requirements of the subscriber should be met as far as possible by the telephone engineer, whether the service required is long distance or local, in a small community with a comparatively small number of telephones, or in a great city of large area with hundreds of thousands of telephones, any two of which may be connected together in the least possible time, and in the operation of which, without question, there will be a decided peak load during certain hours of the working day which must be taken care of if the service provided is satisfactory.

Arthur Bessey Smith: The paper presented by Mr. Clement is very interesting in that it presents clearly a very essential question involved in exchange operation. The question may be stated thus. Is the human element necessary and desirable in connecting exchange lines? While every human activity requires human attention to some degree, there are many things which, on account of their nature, may be better and more satisfactorily handled by machinery. Before we can decide whether or not the telephone exchange comes within the automatic field, it is necessary to consider two features, *viz.*, the nature of telephone service and the practicability of selecting lines by automatic machinery. Since Mr. Clement has himself acknowledged the latter point, we may confine our attention to the former.

Telephone service consists essentially in establishing means whereby conversation may be held between two points. This is usually limited to speech transmission by electrical apparatus connected by wires. When we have turned such an arrangement over to two or more people to use, we have rendered telephone service. Since the outfit is usually owned and maintained by a company for public use, a fee is charged whenever it is loaned to any person or institutions. Also because the people must pay for telephone service it demands that the service shall have some degree of quality.

The elements of quality in telephone service are, in order of importance, as follows:

Accuracy of connection, quality of transmission, speed of connection and disconnection, proper treatment and ease of securing connection.

Voice transmission is usually very good in modern exchanges so that for our present discussion we may omit it from the list. This leaves the following:

1. Accuracy of connection.
2. Speed of connection and disconnection.
3. Proper treatment.
4. Ease of securing connection.

Theoretically, it might seem that the human element is indispensable to the rendition of good service, but practical experience has shown that almost all of an operator's work is inherently mechanical, requiring no judgment. In the total of a day's work, the calls which require intellect are so few that they can be cared for by very few clerks.

The automatic switchboard can render excellent service in all of the elements named above. These I will discuss in detail.

The transmission of a number by mechanical and electrical means is far more accurate than by voice. In the messenger company analogy, used by Mr. Clement, the public would not entrust its business to such a concern if address of a parcel were given to the messenger orally .Nothing but a plainly written address will do. There are many chances of mistake in oral transmission, both on the part of subscriber and of operator. The act of spelling out a number with a calling device is naturally conducive to accuracy since it is done through sight and touch, the two senses upon which man places his greatest reliance.

From the standpoint of the subscriber, automatic service is quicker than either manual or auto-manual. The time from the initiation of a call to its connection through the apparatus is from a third to a half as long with automatic as with auto-manual. The saving when compared with manual service is even greater.

It may seem strange to compare a human operator and a switch as to " treatment of the public," but the relation exists and is very real. Far from being " the principal ground for confidence " the operator touches the public with a treatment as variable as her moods. The automatic switch treats the public with uniform courtesy—the courtesy of implicit obedience. In all but a limited number of cases no subscriber asks more than that his desire for a connection shall be quickly and accurately made, which service the switch certainly performed. The automatic switch accords the public the best possible treatment.

Generally speaking, to relieve the subscriber of all work possible is not necessarily inconsistent with the highest type of service. The highest and best service is rendered when we most completely meet the subscriber's desires and needs. Further, not all the labor of making a manual call is felt by the hand, for the brain and the organs of speech are involved. Compared with the oral transmission of a number, it is a relief to turn the dial. The subscriber does not feel it to be a burden, but regards it as an efficient means to an end. He asks for *results*.

To sum it up, I believe that the amount of telephone traffic which requires direct access to human intelligence is so small as to be negligible. The small class of calls which requires special attention should be handled as at present by clerks, who are not operators. For the great bulk of traffic the human operator is not only unnecessary, but a positive hindrance to good service. People desire *service*, that is, telephonic connection, which the automatic switch has the special capacity to give. The perfect rendition of this service has established among automatic users a feeling of strong confidence.

Henry P. Clausen: Mr. Clement states that in the manual switchboard an operator can attend to from 280 to 290 connections per hour. While I do not think that this figure is any too high, the records of the average exchanges throughout the country will run more closely to the 250 calls per hour figure, and that only during the busy ten hours of the day. During the peak hour, however, operators will frequently go as high as 400 calls per hour, and for short periods an observation has shown that an operator can answer as many as 425 calls per hour. 300 to 330 calls during the peak load is not at all unusual. In fact, in one of the exchanges mentioned by Mr. Clement the writer has found a record showing 288 calls per operator's hour, and it is interesting to observe that 63 operators on duty at the same time were averaging this number of calls.

According to Mr. Clement's statement, only 31 per cent of the total cord circuits are in use at one time during the peak load. The writer does not think that this can be absolutely correct, and, in fact, upon consulting the records of one of the exchanges cited, 63 positions were in service, each equipped with 15 cord circuits, and out of a total of 18,200 calls during the peak load, allowing three minutes per conversation, 96 per cent of the connective means were in service; and, taking the run of calls during this particular day, out of a total of 189,000 possible three-minute conversational connections, 135,000 calls were taken care of, which then gives us about 70 per cent of the connective means in service during a continuous run of ten hours.

Another statement made by Mr. Clement refers to the expense of operating the trunk circuits in a certain exchange, which, he says, amounted to 31 per cent of the total operating charge. As Mr. Clement gave the name of the exchange, the writer was in position to examine into the records and found the following: Out of a total of 21,300 calls, requiring 198 operators' hours for handling them, 6500 were trunked outward, which equalled about 30 per cent. The incoming trunks amounted to something over 5600 calls during the day, and these were taken care of by 58 B operators' hours. Mr. Clement probably had the above records before him when preparing his statement, and therefore did not carefully consider the local conditions, for, when it is learned that in this particular exchange the B operators, instead of answering calls of from 350 to 400 per hour, as is the usual practice, were only answering 98 calls per hour, it will reveal to every traffic man a serious condition of affairs, requiring correction.

In discussing full automatic exchange operation, Mr. Clement suggests that irresponsible persons may call anyone and cause a great deal of annoyance without danger of detection, and, as I understand the description of the automanual system, the same difficulty remains, for, when an automanual operator sets up a connection and presses the starting button, this connection passes beyond her control and she is not able to detect any improper use of the telephone.

I believe that it is admitted that in the full automatic exchange one attendant is required for every 700 subscribers, these attendants taking care of the automatic switches, supervising them while the exchange is in operation; but it is not brought out by Mr. Clement that the automanual system, employing, as I understand it, the same number of line switches and trunking switches as the full automatic, must also employ the same number of attendants. This would very seriously increase the operating expenses.

As to the statement that one day's training is sufficient for an automanual operator, this may require some qualification in the direction of understanding how efficient such an operator may be for performing the difficult feat of handling subscribers calling for service.

It is further stated that all operations in the automanual system are standard. How are the different classes of service taken care of; for example, pay-station, measured service and flat rate service. Such calls as require the recording of subscribers' numbers should prove very difficult in the automanual system, for the operator has nothing before her to indicate the calling subscriber's identity, and it would appear difficult to obtain it other than by inquiry, and then at the risk of being given the wrong line number or wrong information. At any rate, pay-station and measured service calls, which in many exchanges run into quite a large percentage of the total number of subscribers' calls, cannot be handled at the high rate claimed in Mr. Clement's system.

In the comparative work units submitted, and based upon the number of movements of the A operator in handling a local call, a more equitable division could have been made, but Mr. Clement makes the serious error of completely ignoring the presence in the manual switchboard of overlapping operations upon the part of an operator. Each distinct operation is said to be performed to the exclusion of any other; this, while it is true for the automanual system, is not the experience in manual operation, for in the manual switchboard an operator can respond and does act upon audible and visual signals practically simultaneously, and at the same time each hand may be used for a different operation. As a matter of fact, it would be impossible for an operator of a manual switchboard to handle 300 connections per hour were the overlapping not present, for telephone calls do not always accommodatingly originate in equally timed periods as they should if each operation were distinct and separate from every other operation, for at times three, four, or more calls appear upon a position at practically the same instant and a great many of the answering operations are then performed practically simultaneously.

It is at this point that I want to bring out one of Mr. Clement's suggestions, "When a subscriber calls, if he receives a quick response, he is satisfied, even though a slight delay occurs later," for it is the overlapping operations which permit the operator of the manual switchboard to produce what we call a three-second's service. An operator cannot possibly complete, say, four calls in their entirety in three seconds' time, but she can answer the calls in that time by quickly inserting the answering plug into the jack and calling for number.

In the automanual system, as understood by me, an operator is expected to answer 1,000 calls per hour, which in an exchange originating 5,000 calls during a busy hour means five operators. What is the result when—as it is entirely probably—20 subscribers' calls are received within a given second or several seconds' time. According to the figures upon which the automanual operation is based, it takes an average of 3.6 seconds for an operator to respond to and set up an automanual connection;

therefore, in order to answer the 20 calls, it will require 72 seconds time; dividing this by the five operators who are not able to perform any overlapping operations, it appears that at least 14 seconds must elapse before the last one of the 20 calling subscribers is disposed of; and with more than 20 calls the delay would be much greater. This, I believe, is one of the most important points not discussed by Mr. Clement.

C. S. Winston: Mr. Griswold brought up the question of the method of handling reverting calls in an automatic system. Most of you probably know that a reverting call is a call from one station on a party line for a second station upon that same line. In manual equipment this does not present any very difficult problems, but in the automatic it is a very different thing. In the three-wire automatic the problem has been solved and it is possible for one party to call for another on the same line without knowing that he is calling for a station upon the line upon which his station is located. In the two-wire automatic, using automatic ringing the problem is entirely different. Up to the present time, I believe, no satisfactory means has been found for accomplishing this result, and hence it is necessary for a subscriber to know that the telephone of the man with whom he wishes to talk is upon his own line. If he does not, he will call and receive a busy test just the same as if he were calling for a separate line which was in use. The number of calls, however, of this sort, I understand, is not very great, and I do not think that any particular trouble has been experienced with that difficulty.

No telephone system is or ever will be absolutely without defects, or entirely ideal. This refers to manual equipment as well as automatic equipment. In the automatic system, if a subscriber upon a party line takes off his receiver at the time the second subscriber upon that same line is signalling, trouble is sure to be met as the impulses which are sent subsequent to the removal of the second receiver will be lost and the proper station will not be called and possibly no station will be signalled. I see no way in which this defect can be overcome. It is one of the defects which seemingly are inherent in automatic equipment.

In automatic equipment difficulty is met in the handling of measured service. This is true either when service meters are used at the central office, or nickel boxes at the subscribers' stations. That is, if a party is called and another party responds the charge is made just the same as when the call is properly completed.

Mr. Griswold also brought out another point in regard to two subscribers plugging into jacks of the same line simultaneously in the system which I referred to as the automatic distributing system. I don't think that trouble will be met with on this account. In the system which my company has laid out, more or less in detail, there is a relay in the cord or trunk circuit which operates as soon as the plug is inserted into the jack of a line and if two plugs are inserted into two jacks of a line simultaneously, it would be necessary for them to operate at the same instant before trouble could result. I don't think the chances for this to happen would be as great as the chances in the manual system of missing the busy test and plugging into the jacks of a line already in use.

It was suggested by Mr. Miller, I believe, that a possible solution of the problem might be in the combination of the semi-automatic and the full automatic. It hardly seems to me that this would be a satisfactory arrangement. In communities where the plan has been used of operating both common battery and magneto telephones the results obtained, I understand, are very unsatisfactory. If a man has one type of telephone and a friend of his one of the other type, he is apt to make up his mind that he prefers the telephone which John Jones has and he is not satisfied until he gets it. It seems to me that trouble would be met with if this suggestion of Mr. Miller's were followed.

Such an arrangement would complicate the central office equipment, require extra apparatus equipment and hence the expense of maintenance would be increased. I don't think the service would be as satisfactory as if either one of the two systems were used alone.

It has occurred to me that there may be confusion due to the fact that in my paper I referred to the " semi-automatic system " and Mr. Clement referred to a system, practically the same, as the " automanual system." There are no differences as far as operation goes and the differences which exist are all merely differences of detail. The automanual, or semi-automatic, is nothing more nor less than an automatic system in which the dials are removed from the subscribers' stations and operators at the central office do the work which is done by the subscribers in a full automatic system.

Very frequently in semi-automatic, or automanual there is more or less trouble due to the fact that after the connection has been established, as Mr. Clement has already stated, the operator is entirely disconnected from the circuit. If for any reason the subscriber desires, after the connection has been established, to call the attention of the operator, or perhaps I should say to converse with the operator, the operation of the switch-hook will disconnect the apparatus entirely and instead of calling the attention of the operator he called originally, he may get some other operator. This may cause trouble, although I understand not a great amount has been experienced in the three or four places in which the automanual is now in use.

It does not seem to me that automatic equipment is likely to be used in small towns. I don't think there is likely to be any great conflict of opinion in regard to this point. In small plants the cost of maintenance must necessarily be low and the original cost of automatic equipment, and the cost of maintenance, would in all probability make it prohibitive.

Mr. Clement stated in his paper that in a telephone system subscribers pay for service and hence should not be bothered with duties which should really be done by the operator. I hardly agree with him in this respect. I seems to me that if the subscribers do not object to performing this work, and advantage is gained by using full automatic, it is certainly justifiable to do so.

This brings us up to another point. One or two of those who took part in the discussion have stated that they thought this whole subject would result in the adoption of the system which would give the best service. While, of course, service will play an important part, yet I think it is a secondary consideration. The foundation of any business is laid upon the returns which are expected from the investment; that is, you get down to the old proposition of the almighty dollar. If it is found that automatic equipment can be bought and operated at less expense, and hence will give greater returns on the investment than manual, it is the system which will be used.

In places in which automatic has been employed, the subscribers have shown that they are willing to operate the dials without complaint and it seems to me that the operating companies must decide which system will meet their ends best, and install that equipment universally. The service, of course, will be improved, and kept at as high an efficiency as possible; but it all boils down to the fact that it will not be improved unless an improvement will increase the returns upon the investment.

E. E. Clement: The work which I present is individual work, and I have tried to present it in an individual way. I have tried to look at both sides of this subject impartially, and having gone into the question very thoroughly on both sides, I long ago personally decided in my own mind that the semi-automatic principle, in whatever form embodied, would necessarily be used in the future. Of course I have advocated that ever since. Now, a man ought to be able to give some reasons for the faith that is in him, and that is what I have tried to do in my paper, and shall continue in these remarks.

Mr. Keller read a very interesting letter from a friend of his in the Siemens and Halske Company in Berlin, in regard to their work over there. I would not refer to this except that Mr. Keller in discussing it stated that he had been surprised to learn that the Germans had been developing along my line. Dr. Raps and Mr. Grabe, of the Siemens and Halske Company, have been in touch with me. They were over here several years ago with a party, and were given every opportunity to see my work. They are desirous of introducing these improvements in Germany, and I mention this so that no false impressions will arise as to the situation. I do not believe that the Germans or any other foreigners have done any substantial work in developing the automatic or semi-automatic systems in any form in which they appear in this country.

Mr. Keller also referred to changing what he called "half-automatic" to full automatic, and to "mixed" systems. I tried to make clear yesterday and in my paper that in my automanual system there is one vitally distinctive feature, (among a great many original features) which is not found in any full automatic system, or in any of the ordinary so-called "semi-automatic" systems, of the type referred to by Mr. Winston. I refer to the use of an operator's trunk, separate and distinct from the talking trunks which are used to connect the subscribers for conversation. Disregarding this, the basic principle of semi-automatic amounts to no more than moving your senders in from the subscribers' stations to the central office. There is no reason, either technical or psychological, why a mixed system should not be employed if it is wanted; that is, we can arrange our circuits so that all the connections are made by automatic switches, but some of the subscribers can have senders and work the switches direct, while the rest of the subscribers are handled by the operators. This condition would actually exist during the process of changing over an existing full automatic equipment to automanual, which we can do very readily, but for permanent use I would not care to recommend such a system.

In considering my individual operator's trunk, it must be remembered that any semi-automatic system which ties the operator to the talking trunks necessarily loses almost all the advantages of operator-centralization. The key to the solution of this problem is in the provision of separate operators' trunks, which are automatically connected to and disconnected from the talking trunks, and which can be made of any length desired, so that the operators can be centralized or shifted around, or divided into different centers, or otherwise handled as traffic conditions and the discipline of the operating companies may render desirable. This, with a number of other features, are broadly new and peculiar to my automanual system. I know quite a number of these features have been taken up and followed by others as we have developed and announced them. I am aware that other people will try to get into this line of business, but these are commercial questions with which the Institute is not concerned, and I am sorry that others have brought them up. At the same time, I am glad of this opportunity for an answer on my part. I may say that I believe, commercial and legal questions being disregarded, if every telephone manufacturing company started making similar apparatus, the supply would not exceed the demand in the next ten or fifteen years.

In this same connection, the matter of making a recall has several times been referred to. It is stated that if the calling subscriber gets his connection and the operator is cut off, the subscriber cannot call her back. This is true, and no trouble can or does flow from it, the facts being quite contrary to Mr. Winston's statement this morning. In my system the subscriber hangs up his receiver, is instantly cleared out, takes down his receiver and instantly gets an operator, who may be the same or another. The whole operation of hanging up and taking down is practically instantaneous, much quicker in fact than any ordinary recall could be. What is the use of tying the operator up and interferring with the work. If a man wants to make a recall, he can do it better by making a fresh call. If he wants to report some trouble, or to make another call, he can get the operator or he can get the trouble clerk, without delay.

Reference has been made in the discussion to the full automatic system operated through subscribers' metallic lines without grounds. As I have stated, I can operate my central office mechanism from the subscribers' stations, over metallic circuits, and in fact I may state broadly that I can do with this system anything that is done or could be done with any full automatic, for the obvious reason that I have the full automatic equipment at the central office; and I can also do anything with this system that can or should be done in a manual system, for the obvious reason that I have operators at the central office, while the subscribers' equipments and line connections are the same as in the manual system. In fact, when I started, a good many years ago, to attack these problems, I first of all worked out those which are common to all automatic practice, among them the metallic circuit problem, which seemed very difficult in the beginning. Years ago I was able to make a report with blue prints of two wire metallic circuits which had been then successfully working automatic switches for a long time, using timing solenoids instead of the magnets referred to by Mr. Winston. In that full automatic circuit I also had selective automatic ringing, which has been successfully working ever since, having been grafted into the automanual circuits. I believe the principles thus discovered are indispensable for good practice.

Mr. Griswold, and some of the other speakers, on the question of reliability, have referred to the question from the subscribers' standpoint alone. I think we must look at this problem from every standpoint, not only the subscriber's but the company's, and also as Professor Cory has said, the standpoint of those engineers and their associates who have given their lives to developing these systems. In the practical aspect of the question, there are only the subscriber, who wants service, and the company, which is called on to furnish that service in enormous quantities, and must therefore practice economy as a matter of absolute necessity. Economy however, must be effected without detriment to the service given the subscriber.

I have devoted a good deal of time, in conjunction with Mr. Boylan, to collecting and comparing traffic statistics. If you will read the first ten and the last ten pages of my paper, which are devoted largely to discussion and tabulation of this traffic data, it will save me from going into a lengthy explanation now. In regard to some of my diagrams, particularly Figs. 17 and 19, you will observe that I have shown only two curves for comparison, one the manual curve showing cost of operating, and the other my automanual curve. I did not attempt to plot a curve showing similar costs in a full automatic system, because of a desire to be extremely impartial, preferring to present the figures, as I have in the argument, and leave the comparison to you. My reason for this was primarily that in the full automatic system, you cannot entirely segregate the operating expense from the maintenance and other costs. Now, how the various operating companies employing full automatic systems, keep their accounts, I do not know in detail. I have seen some of their reports and some of the data used in making up their statements, and they are very interesting; but I would not plot a curve without compiling and comparing these to an extent that has not been within my power in the time allowed for preparation of this paper. However, I believe, and I think you will agree with me after reading the figures I have given, that if the automatic cost curve were plotted in Figs. 17 and 19, it would lie between the manual and the automanual curves which I have plotted. I have stated in the paper that the net saving per annum in mere operating expense as such, by the use of full automatic equipment, cannot be more than 50 per cent of the manual operating expense in a system of any size, and that it is probably very much less. This may or may not agree with the facts in all cases. That is for you people to determine. You have better statistics at your disposal than I have. I show a saving however by the automanual over the manual in one given case of 77 per cent (see Fig. 17), and I also show an extreme case which I may state is based on studies in the city of Cleveland, Ohio, of the traffic of both companies which are competing there, in which the use of the automanual system will save 86 per cent of the present manual operating expense. As opposed to this, if the two companies were to trunk direct between their switchboard by manual methods, it would increase their present separate operating expenses by an average of 40 per cent, which makes a total difference in my favor, operating under the same conditions, of 120 per cent of the present total operating expense. The question for you automatic men to determine is, what will you be able to do with your equipment when you meet a similar condition.

Traffic conditions in the telephone business at present are fairly comparable with those in the railroad business. This country has been growing with most tremendous leaps and bounds, and we have not yet reached anywhere near the limit. When you have only a few instruments to handle, it is easy to consider only reliability, and forget the cost of service. But when you are dealing with a city exchange handling from six hundred thousand up to several million calls per day, and those calls cost anywhere from $1.50 up, per thousand (the Cleveland combined figure is $1.96) then it becomes indeed a serious question, and you cannot yield to the subscriber entirely. With the automanual handling these calls at 25 cents per thousand, however, the subscriber should get all the attention he needs. This system is designed to give the subscriber the same grade of service that he gets in the best manual system, that is the individual attention of the operator, and the benefit of her training with all the other benefits flowing therefrom, but at a minimum cost to the company.

One question asked is was what happens if a line is called and the subscriber does not answer, the operator being then off the connection. For this condition I provide a special tone test signal, which comes on if desired after a certain number of rings, or we can handle it through a monitor, or in any other manner possible in the automatic. I preferably provide signals for every condition, which I find the subscribers learn to distinguish very readily. At Ashtabula, we have a busy-back, substantially the same in its functions as that with which you are familiar in your automatic systems. We also have a don't answer signal, but the calling subscriber preferably hears the ringing. We also have a special tone test for the case where the calling subscriber hangs up before the operator gets to him, which she hears when she listens in. We also have an indicating board, with lamp banks, and other signals, so that any condition of trouble or line in trouble can be traced by the wire chief. We also have the other expedients for various purposes with which you gentlemen are all familiar in your practice. Our circuits are very full and complete as to details, and a great many of these are novel, but time forbids my going into them.

With respect to reverting calls, I have no trouble with those. The condition which must be produced when you go to test your own line, which ordinarily would then test busy, is almost obvious. You must produce a neutral condition at the instant of your own test. This has been done in several ways, and we have done it in practice by having the last impulse from the sending machine which works the test relay, also sent back at the same instant to the calling end to reverse the test potential. This applies to a two-wire circuit as well as a three-wire. We test on the tip side usually, and have no trouble at all. I am surprised that Mr. Winston made the statement he did on this point, but presume his information was defective.

I agree with Mr. Winston that the percentage of reverting calls is so small that it hardly pays to take care of it. I took this up with a number of the managers of the larger companies in the east, to see what experience they had; and while there are special test signals available for reverting calls, as you may know, in the old manual practice, these people didn't consider the number of such calls sufficient to make any regular provision for them. The way we take care of them at Ashtabula Harbor is this: There is a master switch at the back of a key set, so the operator getting a call for another party on the same line, can cut on a special first selector and disable the associated secondary selector, so that no other calls can come in on her key set for the time. She then handles that call in the ordinary way. The caller gets his party and then the selector switch is knocked down, leaving only the connector on the line. All it needs is ringing and a battery supply. The battery supply, through one bridge connection in the connector, only, is a little less than normal where you get feed both ways, but, on the other hand, you don't need quite as much, because you are talking through a short circuit. In order to ring past the calling party, you have to tell him to hang up.

You will observe from the tables I give in my paper, that this does not affect the operator's efficiency. The percentage of such calls is very small, although we have quite a party line development in Ashtabula.

Mr. Foster referred to complaints against the operator. I tried at first to eliminate all sounds and all disturbance from the calling circuit after the operator had gotten the number, that is, to prevent the calling subscriber from hearing any of the actuating impulses or ringing, or anything else. We found, however, that silence was a bad feature. A man gets the operator, he gives her the number, and he has no means after that, if there is dead silence, of knowing whether she is doing anything or attending to the line, and if, through mischance, he does not get his connection, there is complaint. We have now arranged our circuits so that a subscriber, after the operator gets the number and starts the impulses, hears those impulses faintly, and he can also hear the ringing. He also knows that the operator is not on the circuit after she has made the connection, and that the ringing is automatic, so that if there is any blame, he attaches it to the other fellow for not answering.

Now, with regard to the condition of strained nerves on the part of the operator, and that sort of thing, in the paper I have taken occasion to show that in this keyboard arrangement by confining the operators simply to asking the number, we relieve them of a very large part of the purely manual strain; that is, we take the actual work to be performed off them and put it on the machines. The work on our keyboards is very light. The touch is more delicate than the touch of a typewriter or adding machine. We have made it as light as is consistent with reliable operation. So we don't have a condition of strain on the operators, and no one operator is any busier than another. Their work is very light, and if there is any complaint coming or any discourtesy or anything of that sort, the operator does not bother with it for one second—she simply pushes two keys, this puts the party on to the trouble clerk, or some one else, and she is through with it. Our operators are confined to just one thing—asking numbers and setting them up; and to that extent they are mechanical; but they have brains, and if there is an incoherent number given or any trouble, their brains get busy. They don't get any complaints and they don't need them.

The question was asked what happens if a cable goes bad or some other condition arises that might affect a whole group of the apparatus. We have special provision for that the same as in the manual or the automatic. We have the same resources so that we can switch off a whole group of lines and put them on to the wire chief or in the hospital or somewhere else, if desired.

In regard to favoritism on the part of the operators, the P. B. X. operators being accessible by means of candy and so on, if not properly fixed giving poor service—there is another feature in the automanual system which I consider of some importance; that is, that the operator does not know who is calling. Reference was made in the discussion of one of the papers to the primary and secondary distribution in Mr. Keith's system; that is, the automatic electric. I have a primary and secondary distribution apart from that of the operators, by which practically any trunk in a very large group can be reached, and it can be arranged so that any subscriber may reach any operator in the whole exchange. That makes it practically impossible for any operator to know who is calling, unless she has a very remarkable memory and the transmitters are very uniform, or the man tells her, and then she is running the risk of the supervisors reporting her. That eliminates the question of favoritism entirely.

With regard to foreign subscribers, it happens that we have had some experience with them. We have quite a foreign population at Ashtabula Harbor, and I don't think we have had one complaint from those people as to the operators not understanding their numbers. This may result from the fact that some of the operators in the exchange—not all of them—were drawn from the native population. I presume they are accustomed to the linguistic idiosyncrasies of the people. In the case of Swedes, select a Swedish operator for them, the same as you have Chinese operators in San Francisco. Before spending forty or fifty thousand dollars extra for apparatus to accommodate these subscribers, better invest in a little foreign assistance.

Another question raised relates to possible defective ringing in case the calling subscriber does not give the number of his party on the line wanted. It is possible to group the lines so that all party lines are segregated; and then if a calling subscriber fails to give the letter or number, the operator can ask him. She repeats the number back as she sets up the keys, and the subscriber would then probably repeat the ringing letter even if she did not ask. Where all the lines in an exchange are party lines, the question would always be asked.

As to the methods of compiling our data: I have a photograph of the Horograph, so-called, made for automobile timing. It is a very interesting machine, and I will be glad to show it after the meeting. It is guaranteed to be accurate to one one-hundredth of a second. All our reports have been based on this and on automatic peg counts. We have an arrangement of the relays so our peg count is taken every day and all the time, and is absolutely accurate. All the calls are recorded, together with the manner and efficiency with which they are handled.

Mr. Babcock stated that introducing the operator was introducing a weak link. I think that point has been answered by some one else, but I am not going to let it pass, because it is, I think, an error. The answer is this: If, as Mr. Babcock stated, and as we know to be the fact in manual systems as well as automatic, a considerable percentage of the troubles reported is due to the subscribers calling, then where can the weak link come in from introducing a skilled and trained and habitually poised operator in the place of the subscriber? I have covered that subject pretty fairly in the paper, and I don't think I will go any further into it, because I have not the time.

As regards the private branch exchange, practically every line is a private branch line. If you subdivide your system they all get the same service, and they all get personal attention, and at the same time you can have if you want private branch exchange operators. I do not think it is as economical or as good practice to divide the group of operators if it can be avoided. Nevertheless, special conditions will sometimes arise. I know in New York we figured on some parts of the city, for instance, in the brokerage district, where the men are too busy to stop for anything. They want to make a string of calls each day at a certain time, and an operator who can give attention to that is absolutely essential. There it pays to put in automatic branch exchanges. One operator handling these exchanges ought to do the work of about three the way they go now, even with the varied calls that would be made on her.

Finally, as to measured service: I can provide special operators, and segregate measured service lines and other different classes of traffic so as to bring them in to these operators; but I prefer not to, sticking always to the basic principle of confining the subscriber's operator to asking the number and setting it up. We only need to loop any class of trunks through a monitor's desk and the monitor then takes care of the special condition. A special operator who can take those things off a regular A operator is an economy, because not doing anything else she becomes very expert at this irregular duty—almost as expert as the A operator herself. In other words, you have an organization of specialists instead of one person trying to do a dozen things. Of course pay-station calls are handled in the same way.

We have also a system of metering specially applicable to this connective system. I refer to the Telechronometer. This is not the time or place for me to go fully into that, but I will state very briefly that in line with my theories on handling the traffic I also have some very definite theories on the subject of measuring that traffic. I do not believe, and I never have believed that the counting of calls, whether they were charged up as answered or not answered, is fair, either to the subscriber or the company. I do not believe, and I do not suppose any of you who are in the operating end will disagree with me, that a flat rate service is any more fair to the company than it was in the days when the lighting companies used to give so many lights for so much a month. If a man chose to burn them 24 hours a day, of course the company was out. In some cases a flat rate promotes increased use of the telephone and an increase in the number of subscribers, but this is a temporary resort only. The Chesapeake & Potomac Company in Washington, for a time followed a policy of inviting people to use the residence phones frequently, and even to ask the neighbors in to use them. Of course the purpose was obvious, and I think it has been satisfactorily fulfilled. But I prefer to measure the service; and I think we do it satisfactorily. It is measured in units called telecrons. A telecron is a unit of time-distance, and I firmly believe that is the logical way to measure telephone service—plus a base charge which should cover the cost of that much of the operator's time and depreciation on the apparatus, and so on, which is chargeable to the mere answering of the call if the called subscriber does not reply. With an apparatus of this kind, the effect is that at the end of the month the meter shows the total service which has been given during the month in telecron units. If a man has talked three minutes over a circuit one mile long, he has three units charged against him—I am speaking roughly. If he has talked ten minutes over a circuit five miles long, he has fifty units against him, and the toll service and everything else can be metered so as to show the total service. We have an instrument which will give the number of calls also if you want to know that. The distance-rate is adjusted by the operator, who may be the subscriber's operator or a special operator, at the time the connection is made, so as to correspond with the character and length of the circuits employed. The time element is controlled by an apparatus which is running all the time at the central office.

Mr. Clausen appears to be the only one who questions the figures given in my paper. These figures were prepared, and all of my generalizations were drawn, with the utmost care. The following explanations, numbered to correspond with marked paragraphs in the Clausen communication, will substantiate this statement.

1. Mr. Clausen lost sight of the fact that the 280 to 290 hourly connections were specified by me as busy hour non-trunked calls. He makes the statement that the average exchange throughout the country shows a record of 250 calls for the ten busy hours of the day. A general statement of this kind without reference to the variation in percentage of outgoing trunked calls is unsafe to say the least. It may be well to mention that while an operator can handle 290 non-trunked calls, she can only handle 200 calls where the percentage of trunking is ninety.

Mr. Clausen remarks also that operators frequently handle 400 and in some cases as high as 425 calls per hour at the peak of the load. As Mr. Clausen does not specify we must assume that they are non-trunked calls. Neither Mr. Boylan nor I have ever seen or heard of an " A " manual operator handling anywhere near this load. It requires no traffic experience for one to pass on this statement as being beyond bounds. Even were we to assume that the subscribers were not required to give a prefix or affix with numbers on all calls, the number of hourly calls mentioned would still be excessive.

The average calls per operator busy hour in the exchange referred to by Mr. Clausen is 262 and not 288 as stated. The number of calls during the busy hour is one eleventh of the total daily calls. Mr. Clausen evidently estimated a lower figure than this.

2. This statement is incorrect in four particulars. First, the busy-hour load is not 18,200 calls but 16,500 calls; second, the 16,500 calls do not represent completed connections but from this figure must be deducted the " busy " calls, calls for the time, etc., which, conservatively, amount to 12 per cent of the busy-hour calls; third, the average conversational connection is not three minute in this case, and inquiry fails to show such an average in any exchange in the country having 7,000 lines or over). The average subscribers conversation in the exchange in question is 98 seconds; fourth and finally, the average length of conversation during the busy-hour is 25 per cent less than the average for 24 hours due to a greater part of the conversation being of a business nature.

The claim we make is that not more than 33⅓ per cent of the cords on a switchboard are in simultaneous use during the peak of the load. The exchange referred to has 63 positions with 15 pairs of cords per position, making a total of 945 pair of cords, 33⅓ per cent of which would be 315 pair of cords.

There are 16,500 calls handled during the busy hour. It has been stated that 12 per cent of these calls represented busy calls, etc., but to be conservative we will cut this figure to 7 per cent leaving a total of 15,345 possible completed connections.

The average cord time is 98 seconds, less 25 per cent during busy hour or 73.5 seconds, which figure represents 49 connections per cord pair per busy hour, multiplied by 315 pairs of cords (33⅓ per cent of total) equals 15,435 calls, or 90 *more connections than are actually handled during* the busy hour.

3. Mr. Clausen raises the point that only 98 calls per " B " operator-hour were handled in the west office of The Kansas City Home Telephone Company, instead of from 350 to 400 per hour which he states is the usual practice. Mr. Clausen is confusing the calls per " B " operator hours with the call per " B " busy hour.

There are several factors, however, which preclude the handling of 350 to 400 calls per " B " busy hour in an office such as that in question, the leading factor being the absence of apparatus at the " B " position which should enable the operator to handle such a number of calls. It is true the " B " operator could handle 350 calls if given the " manual selective ringing service;" 400 per busy hour with " machine ringing," and 500 per hour by utilizing " keyless trunks."

Another factor which determines the number of calls the " B " operator can handle is the number of offices connected with her order wire circuit. With the particular type of apparatus in use at the exchange in question the operator could handle 350 calls provided only one office were connected to her call circuit. This figure would be reduced to 300 calls when a second office was added, 260 when a third office was added, etc. Thus the point that only 98 calls per operator hour is answered shows a condition not unusual and which will be found in any branch exchange connected by order wire to several other exchanges.

4. In compiling the comparative work units we allowed for overlapping operations on the part of the manual operator and the illustration given by Mr. Clausen in which he assumes that 20 calls would land on 5 automanual positions at the same instant can be applied to the manual service. We admit that under a condition of this kind which however, is very far from common, the last subscriber of the 20 would naturally have to wait a little longer than the others. This however is true of any system.

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SOME RECENT DEVELOPMENTS IN RAILWAY TELEPHONY

BY GREGORY BROWN

The standard means of communication on railroads for despatching and blocking trains and transmitting messages for the past 60 years has been the telegraph. Although the telephone obviously possessed some advantages over the telegraph for railroad work, the fact that the railroads had been using the telegraph for such a long period and with such reliable results, made them loath to adopt a new and to them untried arrangement. About four years ago, however, a combination of circumstances arose which strongly focused the minds of railway officials upon the feasibility of the telephone to replace the telegraph for railroad work. The most important circumstance causing this result was the enactment of a federal law limiting the working hours of an operator transmitting or receiving orders affecting train movements, to nine hours. In addition to this, there had been a growing difficulty among the railroad companies in securing a sufficient number of competent operators to take care of the natural increase in business. It was also felt that the efficiency of the railroad telegraph operators had been steadily decreasing for some time, this state of affairs probably being brought about by the attitude of the Telegraphers' Organization toward student operators.

It was estimated that it would be necessary to employ about 15,000 more operators on the railroads throughout the country when the federal nine-hour law went into effect and this large increased expense, together with the difficulty of obtaining good operators, caused the railway officials carefully to investigate the possibilities of the telephone in place of the telegraph, for handling train movements and message work.

Up to this time the use of the telephone by the railroad companies had been somewhat limited. It had, however been in use for a number of years for the transaction at terminals and division points of miscellaneous business between departments and throughout the yards, and also in some cases for the handling of trains in the immediate vicinity of the terminal. In addition to the above, many of the roads have been using the composite telephone in some of their divisions, to assist in the handling of trains and for general railroad business. There have also been two or three instances where the telephone has been in use for a number of years for despatching of trains. As early as 1883 this means of handling traffic was used on the New Orleans and Northeastern Railroad, ordinary magneto telephones being used, together with code ringing. The telephone circuit was about 100 miles in length and consisted of one iron wire, and orders were issued for the handling of four regular trains a day, together with numerous work trains.

The Lake Erie, Alliance & Wheeling Railroad has been operating a line of single track road for a distance of about 100 miles by telephone exclusively for a number of years, with equipment not to be compared with that now available for this service.

The first telephone train wire using improved equipment was installed in October, 1907 by the New York Central between Albany and Fonda, New York, a distance of 40 miles. Shortly after this the Burlington installed a circuit on a double track section and later several circuits on single track divisions. The success attained with these installations conclusively proved that the telephone could be used to advantage for railroad work, and since that time the railroads have been rapidly equipping their divisions with the telephone.

The object of this paper is to outline the requirements to be met in railroad telephone service and to describe briefly the circuits and apparatus developed to meet these requirements.

During the long use of the telegraph by the railroads they have built up an efficient organization for handling trains by this method, and have thoroughly standardized in the method of doing this business. In order to determine the requirements to be met by the telephone, if it is to take the place of the telegraph throughout a railroad division, it will be necessary to examine the methods used and the results obtained by the use of the telegraph.

There are three main classes of service on every division which are performed by the telegraph.

1. Train despatching.
2. Message service.
3. Block wire service.

The train despatching circuit, or train wire, as it is generally termed, extends along one division and is used exclusively by the despatcher located at the division point for issuing orders regarding train movements to, and receiving train reports from, operators along the line. The average length of division is about 130 miles (209 km.), which is divided into a number of sections or blocks, averaging about 20 to 25, there being located at the beginning of each block an operator controlling that block. The length of division and number of operators, however, vary greatly, some divisions being over 250 miles (402 km.) long and having between 50 and 60 operators on the line.

The despatcher has supreme control of each division, in so far as train movements are concerned, and he handles the business somewhat as follows: Each division has its printed schedule of trains, which contains the time of passing all stations and towers, also time and place of meeting for all regular trains, both passenger and freight. In addition to the regularly scheduled trains, there are more or less extra trains to take care of the varying volume of business, and also there are delays which invariably occur, particularly in freight service, due to condition of motive power, time of loading cars, weather, etc.

The above conditions constantly disarrange the schedule and as it is the despatcher's duty to keep traffic moving with the minimum delay, giving preference to the proper classes of trains, such as mail, passenger and perishable freight, it will be readily understood that he is at all times confronted with a complicated problem, the proper handling of which requires great judgment and foresight.

Each of the operators at the block stations has complete control, under the direction of the despatcher, of his block section. It is his duty to report to the despatcher the time of arrival and departure of trains, and also to transmit a large amount of miscellaneous information concerning the cause of train delays, nature and extent of accidents, hot boxes, broken gears, length of time required to repair, track condition and various other items which are factors that the despatcher must take into consideration in planning his train movements.

The bulk of the despatcher's outgoing business consists in giving train orders to one or more of the operators who, in turn, transmit the orders to the proper train crews. A large proportion of the orders are transmitted simultaneously to several operators. The despatcher calls the operators interested and when they are all prepared, he transmits the message, and they each in turn repeat it back, in order that the despatcher may know that his order is properly understood. In addition to the transmission of an order to a group of operators, it will be remembered that the sounders in all the other offices are repeating the same order. This permits every operator on the line, if he so desires, to hear the orders being given and to keep in touch with traffic conditions.

It will easily be seen that it is of the utmost importance that no interruption occur in train wire service, as the despatcher's inability to communicate with the operators would practically result in tying up the traffic of the division. In order to provide for interruptions in service which might occur, due to line troubles, it is customary to loop all the telegraph wires on the line through telegraph peg switchboards located in most of the towers. By this arrangement it is possible, should any portion of the train wire get in trouble, for the operators in the affected district to cut out the defective section of wire and connect in its place a portion of any other telegraph line on the division. This, of course, would interrupt the service on the line which was used for patching, but the importance of maintaining the train wire is so great that any other available wire is used for patching until the defective portion of the train wire can be repaired.

The above describes in a general way the manner in which the telegraph is used in train despatching. We can now specify the requirements which are being met by the telegraph for this service and which the telephone must meet in order to successfully compete. These requirements are:

1. Ability to signal any one of 50 or more stations on a 250-mile (402-km.) line and ability to signal despatcher from any of the stations.

2. Arrangements whereby any number of stations can simultaneously listen in.

3. Means for quickly testing and patching any portion of the circuit which gets into trouble.

In addition to the above requirements, the telephone owing to its greater flexibility can be arranged to permit of other operating advantages not possible with the use of the telegraph. Among these are the following:

a. Provision whereby officials who are not telegraph operators, but who are directly interested in the movement of traffic, as for instance, train masters, yard masters, division superintendents, etc., can listen on the wire and keep in touch with traffic conditions.

b. Arrangements permitting the signaling of stations without interrupting conversation. This feature results in saving a considerable amount of time.

c. Automatic notification to the dispatcher that the station he is calling is receiving the signal.

SIGNALING

The first requirement is the ability to signal any one of 50 or more stations on a 250 mile (402-km.) line.

The problem involved here is selective signaling on a long and very heavily loaded line, and is an extreme condition which has not been met with in commercial practice. When consideration is also given to the degree of reliability required for this service, it will be seen that the development of special apparatus was necessary. The instrument used for this purpose is called a selector and is installed at the substation and so designed that the despatcher at will can cause any selector to operate and close a contact, thereby signaling that station by ringing a bell or causing a signal to be displayed. There are three general types of selectors which have been developed for this purpose, operating on three different principles:

1. Instruments responding only to a certain number and sequence of long and short current impulses or long and short intervals between impulses. In this case the only instrument on the line that would function properly and close its contact would be the one which was adjusted to respond to the particular code arrangement of impulses which were being impressed on the line.

2. Instruments arranged to be started simultaneously by the despatcher and to operate independently but in synchronism with each other by means of local energy at the station. The despatcher's sending device being so arranged that at a predetermined instant one impulse is sent out on the line which at this instant is provided with a path through one selector

contact only, the other selectors either having passed their contacts or not having reached them.

3. Instruments of the so-called step-by-step type which are stepped around in synchronism by a succession of impulses from the despatcher's office, the number of impulses sent determining the station called.

What is known as the Gill selector is an instrument of the first or code impulse type. This device has been used for a number of years to selectively signal telegraph offices, and for this service it is connected in series with the back contact of the telegraph relay and battery. When the proper code is sent over the line, the selector will function and ring the bell, but by using ordinary Morse characters it is practically impossible to reproduce the code and falsely call. As this selector had been pretty well tried out for telegraph service, it was but natural that it should be one of the first used with the telephone. Fig. 1 shows a view of this instrument with the glass cover removed. It consists essentially of a ratchet wheel, an electromagnet whose armature is arranged to step the wheel forward, a retaining pawl to retain the teeth stepped and a mechanical time element whose function it is to permit the retaining pawl to assume either one of two positions, according to the length of the impulse of current.

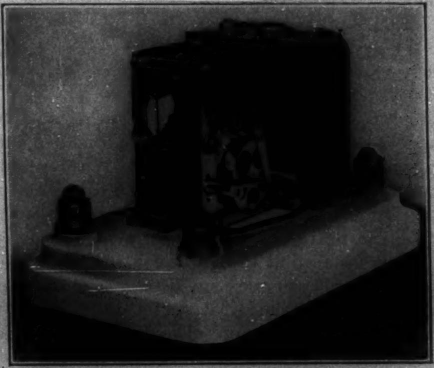

Fig. 1.—Gill selector

The time element is seen at the right of the instrument and consists of a metal wheel fastened to a small diameter shaft so arranged that it can roll down an inclined rod.

The fact that it is the small diameter shaft of the comparatively large wheel, that rolls down the incline causes the descent to take an appreciable time. When the stepping arm is in its upper position it prevents the wheel from descending, but when it moves to the lower position due to current, the wheel starts to roll and will reach its lower limiting position provided the current impulse is of long enough duration. If, however, the impulse is short, the stepping arm will return to its upper position due to the retractile spring, and prevent the wheel from descending its full distance. It will thus be seen that a long impulse permits the time element to function while a short impulse does not.

Fig. 2 shows a diagrammatic view of the ratchet wheel and retaining pawl. The time element wheel, through a system of levers, is so arranged that it permits the retaining pawl to fall in the ratchet teeth to one half their depth if it is in its upper position and to the full depth if it is in its lower position.

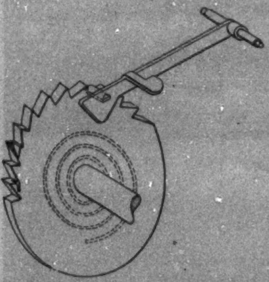

FIG. 2.—Gill selector ratchet wheel

The teeth of the ratchet wheels on the selectors are all cut differently, some are perfect ratchet teeth, some have a diagonal slot sawed in their lower half, while others have the top half of the tooth diagonally cut away. Fastened to the pawl is a semi-circular piece which falls behind the teeth and holds the wheel from returning to normal when the stepping pawl is in its up position, preparatory to making another step. If, however, the lower or upper half of a tooth, against which the piece rests, is diagonally cut away, it will push the pawl to one side and the wheel will return to normal position under the influence of its retractile spring.

In order that the retaining pawl hold each tooth stepped of a given selector, its position with relation to the face of the teeth must be such that at no time does it rest against a portion of a tooth face that has been diagonally cut away. This condition is brought about only in the case of a selector which is being operated by its proper sequence of long and short impulses, and this is the only selector that will close its contact and signal its station.

Fig. 3 shows a despatcher's sending key cabinet with the cover removed. There is a key for each selector and each key consists of a train of gears, whose speed of rotation is controlled by an escapement, and when operated a specially cut code wheel makes one revolution sending out on the line a certain code of impulses.

Fig. 4 shows a schematic diagram of the first type of way-station circuit that was used with this selector. The closure of the contact of the line relay puts local battery current through the selector and steps it around. When the selector contact is made, local current flows through the right-hand spool of the polarized relay closing its contacts and ringing the vibrating bell.

FIG. 3.—Sending keys

The lower relay contact closes the battery through the bell while the upper contact places a shunt on one side of the line around the line relay and through a one-tenth microfarad condenser and vibrating bell contact. This shunt through the vibrating contact introduces a tone on the line and is heard in the despatcher's receiver, thus notifying him that the station bell is being rung.

In the first installations of this type of apparatus the line circuit arrangement was as shown in Fig. 5. It was thought advisable to use a line relay at every station and operate the selectors and bells by local battery. In order that the sending impulses might not introduce enough niose in the receiver bridges to interfere with conversation while the despatcher was signaling and also to permit each line relay to receive the same amount of current, a grounded simplexing arrangement was used for signaling, the relays being placed in series with the line. Relays at alternate stations were connected in opposite sides of the line, so as to maintain balance as nearly as possible. With ordinary relays placed in series, the transmission loss would, of course, be very considerable. The relays used therefore on the first installations were of a sensitive type having an inductive winding of 20 ohms and a non-inductive shunt of 30 ohms. This was, in fact, a type of telephone supervisory relay, and from a transmission standpoint was the most efficient relay available. Although the transmission loss in the relay was reduced to a minimum, it was still appreciable especially on a long line with many stations and several receivers off the hook. In addition to this, the shunt winding of the relay made a very inefficient arrangement for operation, as, of course, the signaling current going through the non-inductive shunt represented a clear waste. Another objection to this circuit that was found in practice was noise introduced from the grounds and unbalance, as it is almost impossible to balance the line with series relays. Also the effect of lightning on the series arrangement was found to be rather disastrous. The troubles experienced with this

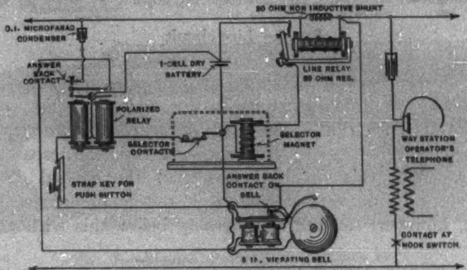
30 OHM NON INDUCTIVE SHUNT
0.1 MICROFARAD CONDENSER
ANSWER BACK CONTACT
1-CELL DRY BATTERY
LINE RELAY 20 OHM RES.
POLARIZED RELAY
SELECTOR CONTACTS
SELECTOR MAGNET
WAY STATION OPERATOR'S TELEPHONE
STRAP KEY FOR PUSH BUTTON
ANSWER BACK CONTACT ON BELL
CONTACT AT HOOK SWITCH
3 IN. VIBRATING BELL

FIG. 4.—Sub-station circuit

circuit finally led to the development of a new circuit, as shown in Fig. 6. In this arrangement there are no grounds on the line and no line relays used. The selectors are wound to 4,500 ohms resistance and placed directly across the line. In series with the selectors is placed the proper amount of tapering resistance, so that the amount of signaling current through each bridge will be the same.

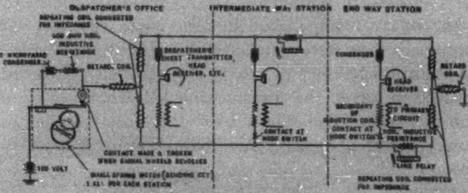
DESPATCHER'S OFFICE
REPEATING COIL CONNECTED FOR IMPEDANCE
INDUCTIVE RESISTANCE
2 MICROFARAD CONDENSER
RETARD. COIL
DESPATCHER'S CHEST TRANSMITTER, HEAD RECEIVER, ETC.
CONTACT MADE & BROKEN WHEN SIGNAL WHEELS REVOLVES
100 VOLT
SMALL SPRING MOTOR (SENDING KEY) 1 KEY FOR EACH STATION
INTERMEDIATE WAY STATION
CONTACT AT HOOK SWITCH
END WAY STATION
CONDENSER
HEAD RECEIVER
SECONDARY OF INDUCTION COIL
CONTACT AT HOOK SWITCH
TO PRIMARY CIRCUIT
NON. INDUCTIVE RESISTANCE
LINE RELAY
RETARD COIL
REPEATING COIL CONNECTED FOR IMPEDANCE

Fig. 5.—Line circuit

The answer back is obtained by including, in series with the selector contact bell and battery, a secondary winding on the spools of the selector. As the bell vibrates it induces current in the selector windings which produces a tone in the despatcher's receiver. With this circuit arrangement the normal current for the operation of the selectors is ten milliamperes. The current, however, can fall considerably below this without affecting the operation of the selectors. The retardation coils and condensers at the despatcher's end of the line are used to cut down the peak of the current wave to such a point that the noise in the receivers while the signal is being sent is not enough to interfere with conversation. In this circuit it is necessary to introduce a condenser in series with the receivers across the line in order that the signaling current may not be shunted through the talking bridges.

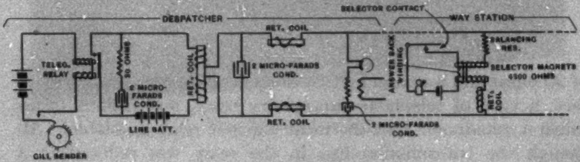
DESPATCHER
SELECTOR CONTACT
WAY STATION
TELEG. RELAY
30 OHMS
2 MICRO-FARADS COND.
LINE BATT.
RET. COIL
RET. COIL
2 MICRO-FARADS COND.
RET. COIL
2 MICRO-FARADS COND.
ANSWER BACK WINDING
BALANCING RES.
SELECTOR MAGNETS 4500 OHMS
RET. COIL
GILL SENDER

Fig. 6.—New line circuit

The second type of selector which has been extensively used, that is, selectors maintained in synchronism by local energy at the substation, is what is known as the Wray-Cummings selector. Fig. 7 shows the despatcher's master sending outfit and Fig. 8 shows the substation selector. The master selector consists of a standard clock-work mechanism, to the second hand of which is attached a contact arm. In the path of this contact there are thirty insulated segments which are arranged so that any one of them can close battery current through a relay when the contact arm engages with this particular segment. The despatcher despresses any of the locking push buttons shown at the right of the figure and then operates the key mechanism shown on the door. This mechanism is merely a retardation device arranged so that when operated a contact is made for a length of time sufficient to operate the relays which start the master and all the station clocks. The substation selector is similar to the despatcher's clock mechanism except that each station is equipped with but one contact arranged to engage with the revolving arm. These contacts at the various stations are adjusted at different angular displacements from the normal position of the contact arm. When the despatcher has started all the clocks simultaneously, it is evident that the contact arm on the master selector will have reached, say its tenth point at the same instant that the tenth selector has reached its point. At this instant there are no other selectors which are on their contact point and due to the fact that the tenth point on the despatcher's clock is connected by means of a locked push button to cause current to flow on the line, the signaling mechanism at the desired station will be operated. Fig. 9 shows the circuit arrangement at the despatcher's office and at the way-station.

FIG. 7.—Wray-Cummings despatchers keys

When properly adjusted this selector has given satisfactory service. It, however, requires one minute to call the thirtieth station.

The third class, or step-by-step selector, is represented in Fig. 10 which shows the Western Electric selector. This device is probably the simplest and quickest so far used for this purpose and consists of two electromagnets connected in series and mounted in a brass frame. Each magnet is equipped with two spools, the cores of one of the magnets being covered with copper sleeves to produce slow action. Fig. 11 shows the schematic diagram of the lever movements. Upon the fast-acting lever is mounted a stepping pawl *A* designed to engage with a ratchet wheel to which is fastened a platinum pointed arm. Mounted on the framework is a retaining pawl *B* designed to retain the teeth as they are stepped. Attached to the slow-acting armature are two fingers designed to engage with the two pawls in such a way that when in the normal position of the slow acting armature, the two pawls will be held out of engagement with the wheel, while in the operated position the fingers will permit the pawls to engage with the wheel. This selector is operated by first placing on the line an impulse of current which operates both magnets. There is then placed on the line a succession of short

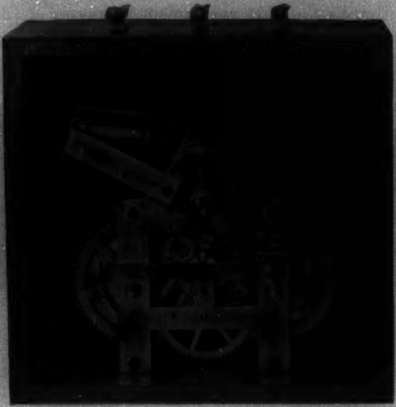

FIG. 8.—Wray-Cummings selector

impulses, which cause the stepping magnet to oscillate back and forth and step the wheel around the desired number of steps. The speed with which these impulses are placed upon the line however, does not permit of the slow-acting magnet releasing. When the desired number of steps are taken, the contact is made and current is held on the line, thus ringing the bell.

As soon as current is removed from the line the slow-acting magnet releases, which raises the pawls and permits the wheel to fall back to normal position under the influence of its retractile spring. When a station is called, say for instance No. 10, all the selectors take ten steps and the selectors at the first nine stations will momentarily make their contacts as they step around; thus momentarily the local station battery circuit is closed at these stations. This, however, will not cause the bell to ring for the following reason: The selector operates at the rate of from 8 to 10 steps per second, and the arrangement of the contact spring *C*, Fig. 11, is such that it follows the movement of the stepping lever and during a stepping cycle makes contact with the contact arm in but a small percentage of the one-tenth of a second necessary to take a step. This action is of such momentary duration that there is no danger of a false signal being given. It will be noted that the contact arm of the wheel in its normal position rests against an insulated contact or stop piece. On the other side of this stop piece is fastened a platinum contact which will engage with the contact arm when the wheel has

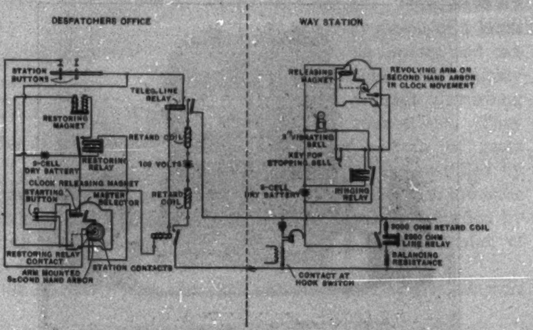
DESPATCHERS OFFICE
WAY STATION
STATION BUTTONS
1
2
TELEG. LINE RELAY
RESTORING MAGNET
RETARD COIL
RESTORING RELAY
100 VOLTS
5-CELL DRY BATTERY
CLOCK RELEASING MAGNET
STARTING BUTTON
MASTER SELECTOR
RETARD COIL
RESTORING RELAY CONTACT
ARM MOUNTED SECOND HAND ARBOR
STATION CONTACTS
RELEASING MAGNET
REVOLVING ARM ON SECOND HAND ARBOR IN CLOCK MOVEMENT
3" VIBRATING BELL
KEY FOR STOPPING BELL
5-CELL DRY BATTERY
RINGING RELAY
3000 OHM RETARD COIL
2500 OHM LINE RELAY
BALANCING RESISTANCE
CONTACT AT HOOK SWITCH

FIG. 9.—Wray-Cummings circuit

gone around to its limiting position. This stop piece is angularly adjustable and permits easy adjustment of any selector for any station. It is sometimes necessary, as will be explained later, to produce a simultaneous signal at all the stations and that is the function of the contact on the stop piece, it being only necessary to send out the proper number of impulses on the line which will cause all the selectors to engage with this contact.

Fig. 12 shows the local battery way-station circuit used with this selector. There are two 40-ohm retardation coils placed on either side of the selector as a protection against lightning. The selector is wound to 3,750 ohms and is connected with the proper taper resistance to produce equal current in all the bridges. When a station is called, contact *A* is made, which closes the local battery through the vibrating bell. The bell is also equipped with a front contact which makes and breaks a 10,000-ohm resistance across the line and gives the despatcher an answer back.

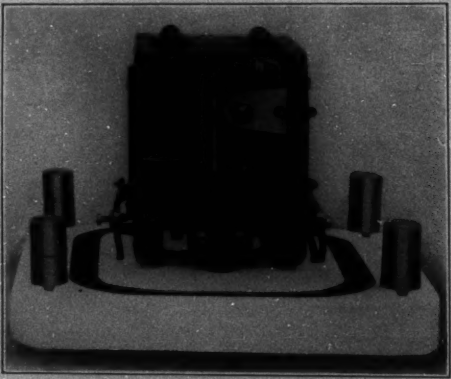

FIG. 10.—Western Electric selector

This selector is also arranged to ring a bell by means of the battery located at the despatcher's office, thus eliminating the local battery at the substation. Fig. 13 shows the apparatus so arranged. When using central battery to ring the bell it is necessary, of course, to have it high wound. In this case, its resistance is 1100 ohms and a taper resistance is used in series to produce the same current through the bell wherever it may be located on the line. It was found that if the taper resistance used for the selector was also used for the bell, the drop in voltage due to the combined current passing through the resistance was great enough to reduce the current to an objectionable extent. Separate taper resistances are, therefore, used on the bell circuit. Fig. 14 shows the despatcher's sending key, one being used for each station. These keys are mounted by means of a latch in a suitable cabinet and can be individually and quickly removed without disturbing electrical connections. They consist of a train of gears whose speed is controlled by an improved silent governor. The contact wheels are the same in all keys of a given type but are adjusted for each station by moving the segments so as to uncover the proper number of teeth for the station desired.

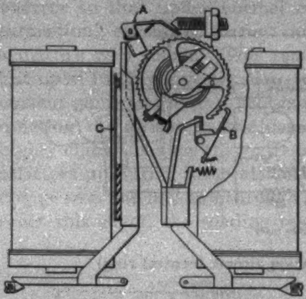

FIG. 11.—Lever movements of W. E. selector

This feature makes the keys universal and as the selectors are easily adjustable to any station, they are also universal, and a spare selector and key kept on hand can be arranged quickly to replace any selector or key which may become defective.

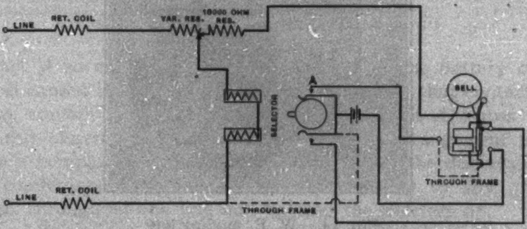

FIG. 12.—W. E. substation circuit (local battery)

Fig. 15 shows the despatcher's and line circuit. The contacts of the sending keys are all arranged in parallel so that the operation of any one will cause the sending relay to operate and place main battery current on the line. Capacity and resistances are placed around the contacts to reduce the sparking. The noise of sending is reduced by leading the battery current through three retardation coils and placing six-microfarad condensers across the line. It was found that if on a despatching wire the line should from any cause break, leaving but few selectors on the line, the current through the selector bridges would rise to such a point, due to the fact that the total voltage was still used, that the selector stepping armature would stay in its forward position when stepping impulses were sent on the line instead of oscillating and stepping the wheel. This was a serious objection as, in case of an accident of this kind, the despatcher would be unable to call the stations between him and the

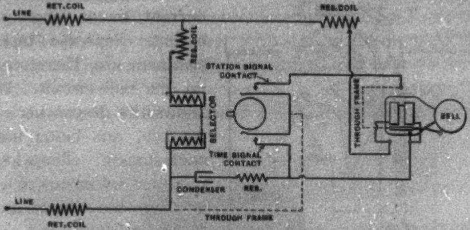
LINE
RET. COIL
RES. COIL
RES. COIL
STATION SIGNAL CONTACT
SELECTOR
THROUGH FRAME
BELL
TIME SIGNAL CONTACT
CONDENSER
RES.
LINE
RET. COIL
THROUGH FRAME

FIG. 13.—W. E. Substation circuit (central ring)

FIG. 14.—W. E. sending key

break. It was found that this sticking occurred more or less in all types of selector operated by impulse from the despatcher's office. The fault was overcome to a certain extent with the Western Electric selector by designing the magnetic circuit of the selector so that under normal current it would be fairly near saturation, excessive current not increasing the pull of the armature very much. This remedied the objection somewhat, but upon further investigation, it was found that with excessive current going to the line, the six-microfarad condensers, used for quieting the circuit at the despatcher's office, becoming more highly charged under this extreme condition, tended to hold the selectors up during intervals between stepping, due to their discharge over the line and through the bridges. In order to counteract this effect, the sending relay was equipped with an extra contact *A* so constructed that the closure of the battery contact *B* caused the opening of *A*, and the instant that contact *B* broke, contact *A* made. In series with contact *A* across the line was placed a 250-ohm resistance. This arrangement provides a comparatively low resistance path for the discharge of the condensers and prevents their discharging to any great extent throughout the line and holding the selectors up.

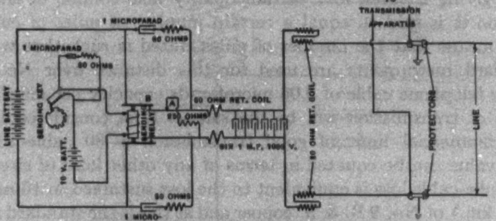

FIG. 15.—W. E. despatchers and line circuit

In addition to the three types of selectors described, there are polarized types of selectors which I believe have been used to a small extent. This type of selector generally employs current of one polarity for stepping and of the opposite polarity for ringing. The objection which has been brought forth against polarized apparatus has been that it is necessary to maintain the line poled in one direction all the time, as a reversal of the line wires will cause all the selectors beyond this point to fail.

The liability of reversing lines due to line repairs, patching, etc., seems to be great enough to raise a serious objection to polarized apparatus.

The foregoing description covers in general the means used by the despatcher for signaling the various stations. The tower operator, when he wants to communicate with the despatcher, listens in to learn whether the line is busy, and if it is not, he merely says " despatcher " in the transmitter. The despatcher wears a head receiver and central office type of chest transmitter and is on the line all the time.

The second requirement which must be met by the telephone as used on a train wire are means whereby any number of stations can simultaneously listen in.

As we will have to refer to transmission values it might be well at this point to explain the units used.

In giving a value to a certain quality and volume of transmission it is said to equal a certain number of miles of cable. This means that the number of miles stated is such that when standard instruments are used for this distance over No. 19 gauge telephone cable of 0.06 microfarads capacity per mile, the value of transmission will be the same. It is considered that the commercial limit of good transmission is 30 cable-miles. This value can be equated in terms of any other kind of circuit. One mile-cable loss is equivalent to the loss sustained in 16 miles (25.7 km.) of No. 9 B. & S. copper and as this is the standard size of wire used on despatching circuits, it will be seen that the line may be 480 miles (772 km.) long before the so-called commercial limit is reached. This is considerably longer than any of the circuits in use, there being but few over 250 miles (402 km.) in length. There is, therefore, a surplus of transmission available which can be taken advantage of in arranging circuits to permit several operators to listen in simultaneously. The loss occasioned by the selector bridges is almost negligible, the impedance to talking frequencies of the W. E. selector being about 90,000 ohms. This value is such, that the loss sustained when forty selectors are across the line is only one mile of cable.

The first form of substation talking circuit used on train wires was the standard local battery circuit, which is schematically shown in Fig. 16. It will be seen that during conversation, the condenser, receiver and secondary of the induction coil are in series. The resistance of the secondary of the coil used was 20 ohms, and of the receiver 70 ohms, a two-microfarad condenser being used in series. The total impedance of this bridge to talking current is approximately 600 ohms, about 300 ohms of which are active for receiving purposes. It is obvious that when a number of these sets are bridged across the line at once, the joint impedance of the parallel paths is very low and the transmission correspondingly difficult between widely separated stations.

The first step towards overcoming this difficulty was to raise the impedance of the talking bridge by the use of a different induction coil, wound with a low primary and a high impedance secondary. This bettered matters somewhat as the higher resistance bridges produced a more even distribution of the talking current from the despatcher's office, and would give better outgoing transmission from the substations. Although the despatcher's voice currents were undoubtedly better distributed among the bridges with this arrangement, still, due to the fact that the bulk of the impedance in the bridges was in the secondary of the coil, the receiver having a resistance of but 70 ohms, the transmission gain was very slight.

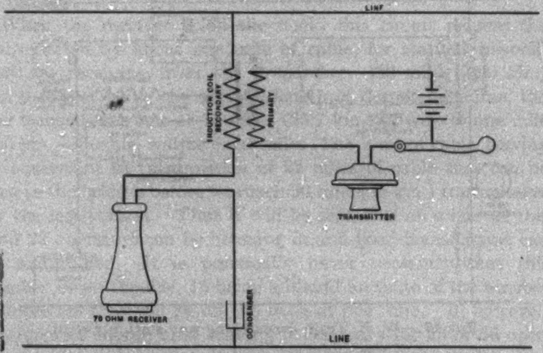

FIG. 16.—Local battery telephone circuit

The next obvious step would be to maintain the high impedance in the talking bridge but put as much of this impedance as possible in the receiver. If this were done, however, the high impedance receiver in series with the secondary of the induction coil would reduce the outgoing transmission from the substation to an objectionable extent. It was then determined that the best results, both for receiving and transmitting, would be obtained by installing a switching arrangement at the sub-station so that when the switch was in one position the circuit was in the best possible condition for receiving and when in the other position was in the best possible condition for transmitting. The circuit developed is shown in Fig. 17, the circuit to the left representing the despatcher's station and to the right the way station.

It will be noted that a non-locking push button is located at the way station and in its normal position the bridge across the line consists merely of a 700-ohm receiver and a one-microfarad condenser. The impedance of this receiver is about 2500 ohms and as the total impedance of the bridge is all in the receiver it is all effective for receiving purposes.

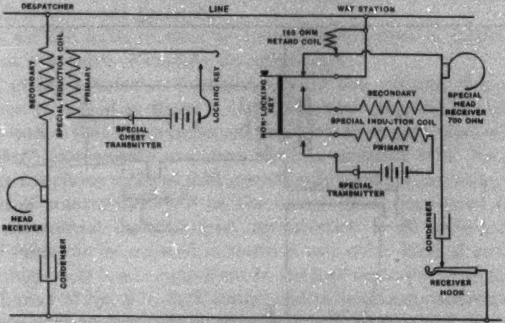
DESPATCHER
LINE
WAY STATION
SECONDARY
SPECIAL INDUCTION COIL
PRIMARY
LOCKING KEY
SPECIAL CHEST TRANSMITTER
HEAD RECEIVER
CONDENSER
165 OHM RETARD COIL
NON-LOCKING KEY
SECONDARY
SPECIAL INDUCTION COIL
PRIMARY
SPECIAL HEAD RECEIVER 700 OHM
SPECIAL TRANSMITTER
CONDENSER
RECEIVER HOOK

FIG. 17.—W. E. Train despatching way station circuit

When the operator wishes to talk he depresses the push button or in some cases a foot switch which closes his local transmitter battery circuit and also connects the secondary of his induction coil to the line. The voice currents generated in the secondary have a path directly across the line in series with the condenser and also a shunt path through the retardation coil and receiver in series. This retardation coil is of about 6,000 ohms impedance and is placed in series with the receiver in the manner shown, in order that the despatcher may break in if it is necessary for him to interrupt an operator while talking. The impedance values are such that the amount of side tone is just sufficient for the operator to distinguish the despatcher's voice if he interrupts and he will release his button in order to clearly understand what the despatcher is saying. The outgoing transmission of this circuit is, therefore, the best possible consistent with the fact that we must arrange to permit the despatcher to interrupt the operator's conversation when necessary.

The induction coil used in the way-station and also the transmitter are especially designed for railway work. The transmitter button is of medium resistance and while not taking excessive battery current still varies the current through a large range and gives good volume and articulation with three cells of battery.

When the receiver is off the hook, this circuit reduces the transmission by about one mile of cable, for stations beyond, that are receiving from the despatcher. 130 miles (209 km.) No. 9 copper being the average length of despatcher's line, the line transmission loss at 16 miles (25.7 km.) of wire to one mile (1.6 km.) of cable, will be eight miles (12.8 km.) of cable, leaving an equivalent in transmission of 22 miles of cable that can be used in the bridges before we reach 30-mile (48-km.) transmission for the last station. Thus it will be seen that on a line of this kind 22 operators can be listening in and good transmission can be maintained. It is practically never necessary that this number be on the line, 15 being a liberal estimate of the number of receivers that will be off the hook at one time. If, however, emergencies should arise making it necessary for 25 or 30 operators to listen in, transmission will be sufficiently good for the transaction of business, even though it is beyond the 30-mile limit.

The requirements of the despatcher's circuit are somewhat different from those at the towers. He must be on the line all the time and the transmission and receiving of his set must be as good as possible, without resorting to the use of a push button for talking and listening, as his time is too fully occupied to permit him to use this device.

The circuit is shown at the left of the figure. A 70-ohm receiver is used in series with the secondary of the same type of induction coil, as is used at the substations, and a one-microfarad condenser in series. The impedance of this bridge is about 650 ohms and it being the lowest on the line, the receiving will be good. This value also permits good transmitting. The switch shown in the figure is of the locking type and opens the battery circuit when the set is not in use. Another form of the substation circuit developed for the way-station is shown in Fig. 18. This arrangement is somewhat similar to the one previously described and contains a push button to operate when talking. Under normal conditions, that is, when the push button contacts are open, the path of incoming voice currents is through the adjustable retardation coil, 70-ohm receiver, secondary of the induction coil and condenser. The impedance of this retardation coil is adjustable by means of a sliding core and the various stations are adjusted with reference to their distance from the despatcher's office, the furthest station on the line having the least impedance. When the button is depressed for talking the transmitter battery is closed and a retardation coil is placed in shunt around the adjustable coil and receiver. This cuts down the impedance of the bridge for outgoing voice currents and still permits of enough side tone so that the despatcher can break in on the conversation. The impedance of the bridge under these conditions, however, is considerably higher than in the previous circuit described and for this reason it is advisable to use more local battery current, as many as eight cells being sometimes used for this purpose. This, of course, is somewhat objectionable in that it tends to decrease the life of the transmitter. The impedance of the receiving bridge with the core all in the adjustable retardation coil, is about 4,300 ohms, and all out is 1,200 ohms. A bridge of 4,300 ohms is equivalent to 0.6 mile-cable loss and 1200 ohms to 1.8 mile loss, or an average of 1.2 mile loss for each station on this circuit.

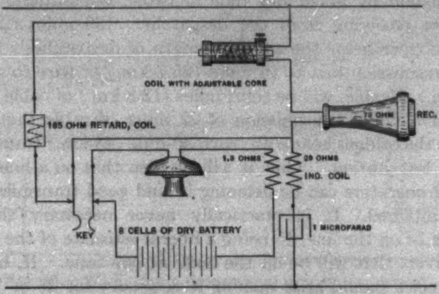

FIG. 18.—Adjustable coil way station circuit

PATCHING

In order to facilitate testing and maintain service on the train wire in the case of line trouble, it is customary to loop the various lines on the pole into every station or every few stations, through patching boxes. A typical box is shown in Fig. 19 and its circuit arrangement in Fig. 20. The wires entering the tower are connected to the jacks at the left, the connection passing through the cutoff contact to the jack at the right and from thence back on the pole line. Two locking keys are provided, arranged so that the selector and telephone set are normally connected to the train wires but by operating the key they are connected to two pairs of cords. When a train wire gets into trouble, the operator can cut off the line beyond his station by inserting any plug in either one of the train wire jacks. This operates the cutoff contact and opens the line. When the trouble is located between any two towers, the operator at the tower nearer to the despatcher throws his key, placing a plug of one pair in the incoming train wire and the other plug of this pair into the wire which he is going to use for patching. He also places one plug of the other pair in the other side of the incoming wire, placing its mate in the other side of the outgoing wire. This will connect the incoming train wires to the outgoing pair of wires to be used for patching. The operator on the other side of the break, plugs in in such a way that the patching wire is again connected onto the train wire. The patching box is equipped with a grounding jack so that any line can be grounded for test.

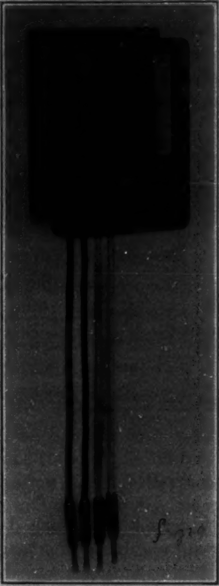

FIG. 19.—Patching box

The foregoing describes in a general way the manner in which the telephone has been adapted for use on train wires. The second class of service in which the telephone is replacing the telegraph is on message wires.

MESSAGE WIRES

A telegraph message wire extends throughout a division and is generally cut in to all the offices on the division. It is used for the transaction of miscellaneous railway business between division and intermediate points. It is also used in a great many cases for sending commercial telegraph messages, when the railroad and telegraph companies employ joint operators. In addition to the above uses, the message wire is usually used for sending time to the various towers. It is extremely important that the clocks at the offices along the line be correct, as even a comparatively slight difference in the indicated time between the despatchers' and substation offices may cause serious results to follow. In order that the accuracy of the various clocks may be regularly checked at a certain time each day, and on some roads twice a day, a certain number and arrangement of dots are sent out on the telegraph line in such a way that they indicate to the various operators the exact time, thus permitting the operators to properly set their clocks, if such action is necessary. From the above it will be seen that the requirements which the telephone must meet for this class of service are:

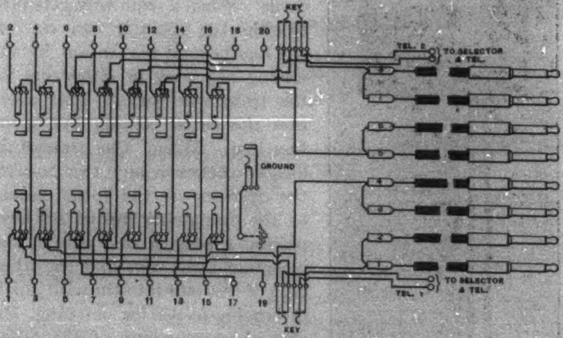

FIG. 20.—Patching box circuit

1. To selectively signal on a line whose characteristics are in general the same as a train wire, but that the selective signaling should be capable of being performed by any operator on the line. In other words, selective signaling arranged for intercommunicating work.

2. The ability to simultaneously signal all the operators so that time may be given.

The telephone has been in use for message work on a number of wires in which all the calling is done by one operator, thereby differing somewhat from telegraph operation. Circuits, however, have recently been developed for inter-communicating work which give satisfactory service. Probably the one having the widest margin of operation was developed in connection with the step-by-step selector and is shown in Fig. 21.

The condensers and retardation coils at the despatcher's end, for reducing the noise of sending, are arranged practically as in the standard train wire circuit. Each substation is equipped with a sending key, so connected that its operation will place impulses on the line from ground through the center of the resistance, over both sides of the line, through the point *A*, thence through the battery and sending relay to ground. The operation of this relay places current impulses metallically on the line and operates the selectors at the various stations, the selector used being the standard type used on train wires. Modifications of this circuit arrangement are in use for this purpose but the difficulty that has heretofore been encountered has been that with a grounded relay, the line leaks are liable to be sufficient to either operate the relay or hold it in its operated position. The glass insulators on a pole line along the right of way of a railway are constantly subjected to the smoke and soot from the locomotives. This almost invariably causes the insulators to become permanently coated with soot and when wet weather sets in, the leaks to ground on railroad lines probably average considerably higher than is found to be the case in commercial

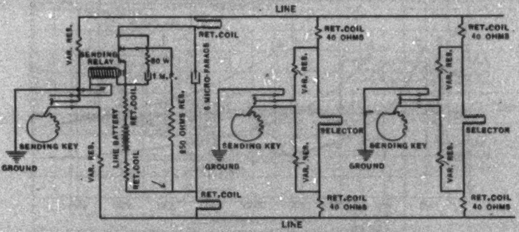
LINE
VAR. RES.
SENDING RELAY
RET. COIL
80 W
1 M.F.
2 MICRO-FARADS
LINE BATTERY
RET. COIL
RET. COIL
250 OHMS RES.
SENDING KEY
GROUND
VAR. RES.
RET. COIL
RET. COIL 40 OHMS
VAR. RES.
SELECTOR
SENDING KEY
GROUND
VAR. RES.
RET. COIL 40 OHMS
RET. COIL 40 OHMS
VAR. RES.
SELECTOR
SENDING KEY
GROUND
VAR. RES.
RET. COIL 40 OHMS
LINE

FIG. 21.—Western Electric Intercommunicating circuit

practice. The circuit shown was designed to neutralize as much as possible the effects of line leakage in so far as it affected operation. It will be noted that when any station is sending, current flows from ground of that station over the upper line wire as shown in the figure, to a normally closed contact of the relay, through this contact to the point *A* on the lower line wire, and then through battery and relay to ground. The contact arrangement is such that the making of the normally open contact breaks the normally closed. This cuts off the current from the upper line wire and doubles the resistance for grounded current, thereby, cutting the current through the relay in half. The relay being in its operated position, this current is sufficient to hold it. As the first effect of line leaks would be to hold the ground relay closed when it was operated, the arrangement shown largely overcomes this tendency. The taper resistances used in connection with the keys at the substation are arranged so as to give the grounded relay the same current from any substation. The curves shown in Fig. 22 show the margins of operation of this system for various lengths of line and operating voltages. For an average line of 130 miles (209 km.) and 160 volts, the line leaks can be as low as 125,000 ohms per mile, without interfering with operation. This is equivalent to about 960 ohms ground leak, which is a value that would seldom be met with in practice.

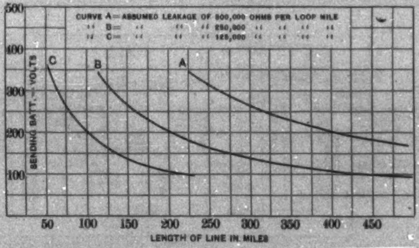

Fig. 22.—Intercommunicating system. Curves show relation between line voltage and length of line. System can be operated over assuming a definite leakage per loop mile (with no readjustment of sending relay).

The manner of sending out time is as follows: Referring to Fig. 12, which is the local substation circuit of the Western

Electric selector, it will be noted that when the selector closes the lower contact, the local battery current goes through the bell winding but in its path is not included the vibrating contact. This will cause the bell to become single stroke in action.

Referring to Fig. 11 which shows the selector, the platinum contact on the stop piece will be made simultaneously on all the selectors when a sufficient number of impulses have been placed on the line. When time is to be sent, the Wire Chief at the division point operates a special key which steps all the selectors around to their time contact point and holds current on the line. The circuit at the division point is so arranged that the contact of the telegraph relay receiving time makes and breaks the current on the message wire. The interval of no current on the line is so short that the slow acting member of the selector does not fall back, but the time contact is made and broken, which taps the bell, and reproduces the signals which were formerly heard on the sounder.

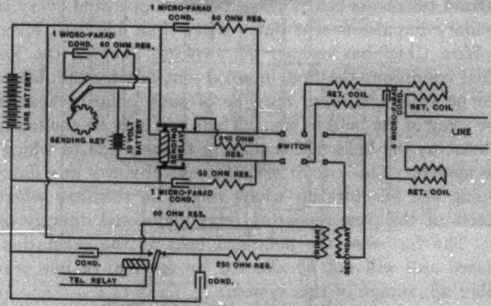
1 MICRO-FARAD
COND.
60 OHM RES.
1 MICRO-FARAD
COND.
60 OHM RES.
LINE BATTERY
SENDING KEY
10 VOLT BATTERY
SENDING RELAY
250 OHM RES.
SWITCH
RET. COIL
2 MICRO-FARAD COND.
RET. COIL
LINE
RET. COIL
60 OHM RES.
1 MICRO-FARAD
COND.
60 OHM RES.
PRIMARY
SECONDARY
COND.
TEL. RELAY
250 OHM RES.
COND.

Fig. 23.—Time sending circuit

This is the method used to send time when local battery bells are used. If the same manner of tapping the bells were employed in circuits where way-station bells are rung by the despatcher's battery, the amount of current required to operate all the selectors and ring all the bells at once, would tend to cause such an excessive current flow that the amount of voltage drop on long lines would be such that satisfactory operation could not be obtained. Another arrangement, Fig. 23, was therefore developed for sending time on the central ringing systems. When time is to be sent on the line, the Wire Chief at the division point throws a switch which connects up the circuit as shown. The secondary of a repeating coil or transformer is connected across the line and the middle point of its primary connected to one side of the main battery, the other two ends of the primary winding being connected to the front and back contact of the telegraph relay, which operates in accordance with the time impulses being sent from the distant point. Resistances are introduced in the leads from the relay contacts in order to limit the amount of current and condensers are used to reduce the sparking. It will be seen that as the relay operates, there will be generated in the secondary of the coil and sent out on the line an impulse or kick, alternating in character. There is placed in series with the selector at each of the substations an ordinary 1000-ohm polarized telephone bell. These bells are operated every time a secondary impulse is sent out. After time has been given and the Wire Chief has opened his switches, leaving the lines in normal condition, the first impulse sent out by the despatcher when he calls a station, may be of such polarity that it will cause some of the bells to tap. There will only be one tap heard, however, as the bells will remain in the position to which they have moved. This circuit arrangement obviates any danger of stepping the selectors up which might be the case where the contacts of the time repeating relay connected directly on the line. The fact that the polarized bells at the substations are unbiased and will not be affected by reversal of line wires, is another advantage of this system.

Up to the present time, most of the railroads are still giving time over the telegraph as there are but few instances of divisions where there are no longer telegraph instruments in the towers. There are, however, divisions on some roads in which the telephone has replaced the telegraph entirely, and on these divisions, time is being given over the telephone circuit.

In addition to the use of the telephone for train despatching and message work, it has also come into very extensive use for block wire service.

BLOCK WIRES

The length of a block wire ranges from one-half mile (0.8 km.) to six or eight miles (9.6 or 12.8 km.) and the service required of the telephone for blocking purposes is merely to maintain communication between two block towers. There are no new features required of the telephone for this work. A great many of the roads are using the existing telegraph wire between blocks for a grounded telephone circuit. This will, of course, introduce some noise in the telephone, but the line being short, this is not generally objected to. If a satisfactory loud-speaking receiver could be produced, it would undoubtedly be very generally used for blocking purposes. If this instrument were used, no signaling device would be necessary, as by simply throwing a key and talking into this transmitter, an operator can call the adjacent tower. This arrangement would also have the advantage of permitting the operator to be handling his levers or doing other work, and still receive the message. Loud speakers have recently been developed and are now being experimentally tried out on a division of one of the roads. The results so far obtained indicate that it will be advantageous to use these instruments for blocking service.

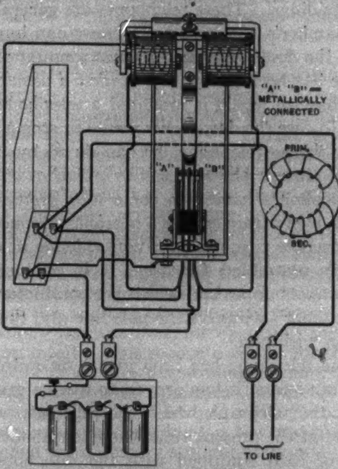

FIG. 4.—Substation circuit

It is very often the case that besides the block wire, there are one or two short party lines reaching from the tower to siding telephones, residences of employees, etc. The hand generator and code signaling is in general use for signaling between blocks and on these party lines. In order to relieve the load of the operator somewhat, an interrupter has been developed, and is arranged so that code ringing can be performed by means of a push button. Fig. 24 shows a schematic diagram of this interrupter. A very efficient type of transformer is used in this instrument, and with six dry cells in the primary circuit, twenty 2,500-ohm bells can be rung on a 500-ohm line.

In addition to the service performed by the telephone on railroads, as has been described in this paper, it has facilitated railroad business in several other ways. Telephones are used very extensively at sidings. These telephones are generally connected with the despatcher's wire and train crews can immediately get in touch with the despatcher, and a great amount of time can be saved. There has been put on the market a semaphore type of signal in the base of which is mounted a telephone and selector equipment. In case the despatcher wants to stop a train and call the conductor to the telephone, he can do so by operating the selector which throws the signal.

Portable telephones have also come into pretty general use. On some roads, every train carries a portable telephone and a line pole. The line pole is jointed for convenience in carrying and can be quickly assembled for use. It is equipped with two metallic hooks at its upper end which the conductor can connect with the despatcher's wires on the pole line and thereby get into communication with him.

Although the telephone has been in use on railroad divisions for less than four years, it has proven to have a great many advantages over the telegraph which the railroads were quick to appreciate, and at the present time, there are about 37,000 miles (59,545 km.) of road equipped with the telephone, and there have been no instances so far in which accident of any kind can be traced to the use of the telephone for railroad work.

DISCUSSION ON "SOME RECENT DEVELOPMENTS IN RAILWAY TELEPHONY," LOS ANGELES, CAL., APRIL 27, 1911.

Kempster B. Miller: The matter of railway train dispatching, discussed by Mr. Brown in his paper, is one of great importance, not only to telephone men, but to railway people and the public at large. There is an impressive mileage of railroads, important railroads, that are now being operated by telephone rather than by the telegraph, and this fact is surprising to those who have not watched and been in close touch with the development of this branch of telephony.

An interesting thing in the discussion of the power transmission papers, day before yesterday, was that some companies had seen fit to build a separate pole line for the telephone circuit, distinct from the power transmission line. That is not because it is impossible to put telephone wires on transmission poles and get fairly good service, but in order to effect an extra precaution to insure telephone transmission at the time it is most needed. In many cases that is not done—I should say in the great majority of cases. Now, if the power transmission companies are, for added security, willing to build a separate pole line for telephone circuits when they already have a high grade line, the question naturally arises in my mind in regard to this telephone railway train dispatching, is it wise for the railroads to load up the talking circuit with the selective ringing apparatus? I see no reason for even suggesting the building of another pole line in the case of railway circuits; but it does seem to me that in many cases the building of a separate copper circuit, or iron if the conditions warrant iron, for operating the selective bells would be warranted. This separate circuit for the operation of the selective bells on the dispatching system, would prevent loading down, with ringing apparatus, a circuit already overloaded with a multiplicity of bridged talking circuits. I understand that some railroads are doing it but that many others have refused to spend the necessary amount of money. In view of the extreme importance, particularly from the standpoint of the safety of the public, I think this phase of the subject worth discussion.

L. B. Cramer: I have not much to say in regard to this paper, as the experience that I have had with the system is not of very long duration, because the line was not entirely completed when I left to come here; but I have a few questions to ask Mr. Brown.

One thing that I do not entirely agree with Mr. Brown in is his statement that the "arrangements permitting the signaling of stations without interrupting conversation results in a saving of a considerable amount of time."

So far as my observation has been concerned, that seems to be more of a salesman's talking point than a reality in operation. Perhaps you might be able to talk while the man is signaling, but once he is finished and the man at the other end has an opportunity to say, "What was that?" and then all of it has to be repeated. Perhaps I have not had enough experience or perhaps our line is not in proper tune to take care of this, but at present that seems to be one thing that does not work out as it is supposed to—that is, the way the company represented the apparatus said it would work.

I have also noticed, in regard to the ringing of the bell at the station called, the sending keys are made of such a size, that if they were made a little larger they would not make a cabinet of extremely large dimensions and the amount of space that can be given to them would then be enough to produce a ring long enough to call the operator. I notice our dispatcher often calls a second and even a third time. In case of substations, where the bell is mounted on a booth, there being some noise in the machines, we have an auxiliary bell that makes plenty of noise and the substations are the stations from which we get the best responses.

In regard to the switches, which have one position for receiving and one for transmitting I have already thought of making some changes in the apparatus because in stations where we have a set that is mounted on a desk, about the second or third day after the telephone is in operation the agents get a ruler or a stick and plug the button. This, perhaps, could be made a subject of discipline and, taken care of in that way, and you could get the result which you are supposed to get by being able to hear better by leaving the button in normal position and only press the button in when you are talking. The agent and operator will do these things and when there is a train coming, or anyone whom they think will see it, they will take the plug out; but ordinarily, they will leave it plugged up so when they want to O. S. a train, they will not have to work the plug.

Another thing that I would like to ask Mr. Brown is in regard to the retardation coils. We made some tests on another railway where their telephone circuit is carried on the same poles as the 33,000-volt transmission system. We made tests of two different companys' apparatus. In the type of apparatus which the author describes I notice they used three retardation coils. On that particular test the man had about 80 miles of telephone line and he was unable to produce results to any great extent, while another company's representative with apparatus similar to this one, but on which he used only one retardation coil, he was able to handle his calling without any trouble and the transmission seemed to be first class. Now, whether there was something in the atmospheric conditions at the time when these different tests were made, or whether it was just a case of some operator's interfering—that is one thing that some of the telegraph operators will try to do. If they know you are trying out a telephone which will do away with their job as telegraph operator, they will resort to almost any means to put the telephone out of commission. We have no trouble in using the telephone in connection with the telegraph, where the telephone is used mostly for handling messages pertaining to freight shipments and dispatching power.

Ralph Bennett: This system was offered to me about two years ago, for use in connection with the transmission line telephone. We did not adopt it. There were a number of questions that came up that the manufacturers could not answer. We have on our telephone line a pressure of about 2,000 volts to the ground, and 600 micro-amperes unbalanced current flow. The line is noisy. When we had trouble on the line we would have additional voltages. The manufacturer could not state how we could repair his sets with the men we had. He could not state definitely his apparatus would satisfactorily select in the presence of those large currents under heavy pressure in this transmission line. I would ask Mr. Brown whether these things could not be handled as the securing of a telephone which will call and select stations for transmission line work is very important.

Ralph W. Pope: Mr. Chairman, there does not seem to be anyone here to take up the telegraph operators' view of the situation.

Now it has been my experience in my fifty years of knowledge of the Morse telegraph, that the people who do not understand it and work it don't appreciate what a beautiful and simple method it is of transmitting communications. It may be of a little bit of interest—add a personal touch—if I tell you that years ago, having some fifty pages of what would now be fifty pages of typewriting, to copy, and several manifold copies to be made, that Mr. Edison, my brother, one other operator and myself took turns in sending and then copying down from the sounder. We did that because it is an easier way to copy it from the sounder than by looking from one page to another. You simply write and the words go in your ear and go out of your pen or pencil onto the paper and that becomes so automatic that in the course of receiving a long press report, as we did during the Civil War, the operator was obliged to take a bunch of carbon paper and change the sheets at the bottom of each page so as to pick up the work when a new batch of sheets were ready, and this involved keeping behind about fifteen words, behind the sounder, and it took all of the next page to catch up with the sender. I am giving you this as an instance of what the telegraph system really is. Now, we take the way station of a railroad and the operator always has to look out for baggage and various things around the place and wherever he is in that room, no matter whether he is called or not, he knows what is going on over the wire. Of course, if he is called, he is obliged to answer. As an instance of what an operator can pick up in that way, I went down from Great Barrington, to Sheffield, expecting to ride back on the passenger train. It was bulletined on the telegraph board " No Report ". I thought I could get to Great Barrington for dinner but I could not find out whether I could and I sat there waiting to get my lunch, growing hungrier all the time. Meanwhile I heard a message going over the line that the train had been delayed, and that they would meet at Canam somewhere below, and so on; and I figured out it would be an hour and forty minutes before the train would be along. So I went to the operator and said, " How late is your train going to be?" He says, " I don't know; I have had no report of it." I said to him, " According to the information I received, they are going to meet at Canam and it will be about an hour and forty minutes wait, and I thought I would have time to go out and get my lunch." Well, he said, " you are a pretty good guesser."

Perhaps what we may call that particular qualification of the telegraph would not appeal to the railroad management, that a man outside could find out how the trains were running. The point I am endeavoring to make in this is, that the Morse system is available to that man wherever he may be walking around the place. He has not got to go and answer a call and put a telephone up to his ear and drop everything else; but he takes that incidentally with his other work. That is simply one of the features of the Morse system that appeals to the railroad telegraph man. You must remember also that a great many of the men who are in active management are practical Morse operators, have grown up with the system, and know what it can do. This question has been discussed before several conventions of the Railway Telegraph Superintendents, and the probabilities are that I shall have occasion to discuss it at their next convention in June. So you will see that there is another side to the question. Here you have a railroad force developed from telegraph operators who are familiar with a system of this kind, and it is the simplest and best thing that appeals to us in carrying on this work. Were a sounder there, I can receive a message sitting here, and I don't have to hold anything to my ear at all. I simply sit down and write from it, and where a man has grown up with it and is familiar with it, he never can get over that love and appreciation of the simplicity of the Morse telegraph system as known to the one who has practiced it, although it is now thirty years since I have done so.

K. B. Miller: I can add my little personal touch there, although a much less skillful operator than Mr. Pope was, and having no right to claim to be an old timer, that it is much easier for me, or would have been in days gone by, to have written down matter taken from a sounder than to get it by telephone. Mr. Pope's remarks suggest a distinct need in railway train dispatching. Some way may be evolved of relieving the despatcher, who is a rather important man, from wearing a harness—I refer to the head telephone. They don't like to do it. The loud speaking receiver has been proposed and tried out rather carefully, and so far as I know has failed. One very ingenious way has been proposed and tried, but has not met with good results owing to poor articulation. It is to use at the despatcher's station a telephone repeater so that the feeble incoming currents could be magnified to produce loud talk in the receiver, and thus relieve the despatcher of the necessity of listening to a receiver held to his ear. This produced plenty of noise but it is articulate speech rather than noise that railway train despatching needs.

C. F. Elwell: In glancing over the paper, I was struck by the last paragraph, "Although the telephone has been in use on railroad divisions for less than four years, it has proven to have a great many advantages over the telegraph." I only intrude on your time to tell you the little experience I have had with the thing 10 years ago in Australia. I went out there to put in block signal systems, and they were already then using the telephone for all of their work. They had a system there in circuits of about 100 miles, just a parallel system magneto and code of signals for ringing. The signals were usually Morse letters, dots and dashes, and they seemed to have very good satisfaction with the phone. They had no telegraph instruments in the office at all. In the matter of calling up, we found lots of times that at certain stations it was almost needless to call. All we had to do was to take the phone off and say, "Are you there?" Those men used to sit with the receiver glued to their ears so they could know all that was going on between all the stations. I just mention this in passing to show you that the matter is a good deal older in other countries. I don't know how old it is there, but I know this was in 1901—ten years ago.

Ralph W. Pope: I might add to my remarks, that the conditions which I spoke of in regard to the railroad service have changed very much within my recollection. When I entered the service, the station agents knew nothing about the telegraph, so in order to have telegraph facilities, the railroad was obliged to have an operator in addition to the agent, so that today we have this different state of affairs where the telegraph operator has grown up to be the agent, and the agent therefore is not necessarily obliged to have an operator at his station, on his staff. This means nothing in large stations where they have several employees, because there is enough work to keep the operator busy; but in small stations it simply means that one man, by his knowledge of telegraphy, his knowledge of railroad work, can be the whole thing.

S. G. McMeen: Some gentleman asked the author the question whether systems of this kind could be used on telephone lines associated with transmission lines? If Mr. Lisberger is present, he can speak of a system of this kind which is in service with a transmission line and distributing system, all within one system, but which has in it all the elements which would result in a long transmission. He could give practical information on a selector line. As to the thought, the author may criticize my asking the question, in this particular case in which Mr. Lisberger is familiar, as it connects stations which he operates, the only difference between a long transmission line and his case, is in the line. It is not in the apparatus or in the operation of the apparatus. Therefore, the problem becomes this: If with the system he has he had a longer line and a greater exposure, he would have a practical answer to the question which has been answered. Now, if the lines were longer and had a greater exposure, what new difficulties would be introduced? Only these: that the greater exposure might make that line noisy if it were not well balanced. That is to say, the only features which might make it unsuccessful in that case would be line features. And if we can build a telephone line which will be quiet during reasonable perfection of the telegraph line which it accompanies, then we can have good service over it. Such lines as that are operating every day successfully. So far as the telephone line and telegraph line are in normal condition, then successful operation ensues. There is nothing in the selective apparatus or in the special features of the dispatching circuit which would cause that line to be less easily perfected and operated than a telephone bridging apparatus. Therefore I would like to hear Mr. Lisberger speak of this line as to its automatic and rapid selection, which represents everything that is of a new character as to which the gentleman asked.

Ralph W. Pope: I wish to express my appreciation especially of this telephone session. Perhaps the Institute has been criticized more severely by some of its members upon this telephone question than any other branch of electrical engineering, as to why it was not giving more attention to the telephone. As you know, that means, why have we not had more telephone papers? I think that this question has been answered—that for the first time we have had Mr. McMeen as an active member of the Telephony and Telegraphy Committee on the Pacific Coast where both great systems of telephony are in operation. We have had Col. Reber as chairman of that committee and he has taken a great deal of interest in this subject and has added to it a great deal by reason of his great familiarity with it due to the position he holds in the Signal Department of the Government.

I must admit I was surprised at the number and quality of this group of telephone papers. I think that great credit is due to Mr. McMeen for his activity in getting them together. I wish to say further that we have had telephone papers before but they never have been discussed so thoroughly by people who were familiar with the various systems in use. This meeting, suggested by Mr. McMeen, for this year, to my mind marks an epoch in the development of the Institute's treatment of telephone engineering. It will be up to us, wherever we may meet hereafter, to endeavor to attain this standard.

J. A. Lighthipe: I have been out of the telephone work a long time but I feel like our beloved Secretary, Mr. Pope, no matter how long he is away from the old original Morse, he still loves it. It is the same way with me in the telephone work. I still love it and try to follow it.

In the old days of the telephone, when it first started, the best receiver we had was what we called a crown receiver. It had six magnets screwed on the back of a handle, and was found to be wonderfully improved by dropping off five and using one. Then the only carbon buttons that were used in the country—we must give Mr. Edison the credit of being the first man who really used carbon buttons on his transmitter—were made in a small shack in the rear of the laboratory at Menlo Park. Mr. Edison could not use commercial lamp black for making the buttons so he made it by smoking kerosene lamps. He had about fifty of these lamps with a V cut out of the center of the wick to make it smoke, and kept the chimneys turning around until they were full of lampblack which was scraped out later.

The smoking process was attended to by an old Irishman who was possessed of great skill in picking up a lamp when it was on fire and throwing it out of the open door. The old transmitter was made of two brass buttons the faces of which were covered with platinum, and a carbon button pressed in between them. At that time it completely revolutionized the telephone business. It was the first time we could talk any distance at all and it really opened the commercial field for telephone work.

Mr. Edison, at that time, was quite deaf. Today he is even more so. It is very hard to talk to him. He could hardly hear the old Bell telephone; even with the carbon transmitter. It was hard work for him to understand what was said at the other end. He therefore tried to invent, or did invent a loud speaking telephone. Very few of you have ever seen one, although they are very simple to make. They consist of a chalk cylinder made by pressing precipitated chalk and afterward turning it down to one inch in diameter. Upon the surface of the cylinder rested a small stylus tipped with palladium. The end of the stylus was fastened to the center of a mica diaphragm. This cylinder was continually rotating and when the telephone was properly adjusted the sound coming out of the receiver was considerably louder than that going into the transmitter; you almost invariably had to pull your ear away when you were talking into it. I don't know that the principle of that telephone has ever been thoroughly understood. When a current passes through the stylus to the cylinder, the tension is released. In turning the cylinder the diaphragm was continually pulled in one direction. As the different waves passed through the chalk the stylus would slip so that the mica diaphragm in the receiver would practically duplicate the motion of the diaphragm in the transmitter. This telephone lasted only a few months. I don't think it was ever introduced in this country. They tried to put it in use in London, but today it is simply laid aside as one of our curiosities.

When the Blake transmitter came out, it was the starting point of all our telephones. It was adjusted so beautifully that you could stand off five or six inches from the transmitter, whereas before you had to talk right up close. The old Blake transmitter probably has done more good towards the universal adoption of the telephone system than any one thing.

In closing I will simply state that I am very very glad to meet the engineers of the telephone convention here. I have followed up, as far as I could, in my crude way, what wonderful improvements they have made. Mr. McMeen was kind enough to show me the first automatic machine I ever saw. That was at Fourth and Market Streets in San Francisco right after the fire. I was simply astonished at the magnificent mechanism of that machine. It was almost human in its hunting up a free trunk, selecting the number, either getting the subscriber or answering back that it was busy. I had no idea up to that time what a wonderful development had been made.

S. J. Lisberger: The telephone system which we have in use in San Francisco is not in any wise connected with a long distance transmission system. The system of the San Francisco Gas & Electric Co. is that used by most companies in city distribution work, namely, a main generating station with a number of substations. In San Francisco we have nine substations and one generating station. We were confronted with the problem of quick despatching between substations in times of trouble. Our ordinary system of telephone communication is a central board in our main office building on Sutter Street, from which point lines radiate to stations and substations. There is always an operator at this main switchboard, day and night. It was therefore necessary if an operator at substation B wanted to get into communication with substation C, to get into communication with the main office first. If we lost a bank of transformers, or a small section of line came down, or in the event of serious trouble to a substation, such as we had after the San Francisco fire, there would be so many calls coming into the main board, that the operator could not give time and attention to the substation calls, and very often we found that if one substation could only get into communication with another substation the trouble could be very quickly remedied, whereas we were often delayed five or ten minutes. The solution of the problem was to get quick communication between substations. The system we finally adopted was worked out for us by Mr. McMeen and was an automatic system. We had objections to an intercommunicating system of our own due to the fact that it must be attached to our poles or in our conduits and that was open to the objection that if we had trouble it was entirely possible to lose our entire communicating system. The wire system, belongs entirely to the Home Telephone Company; is carried on their own lines, in their own conduit systems, and is entirely independent of the system we have in operation; all that is necessary for one station to get another is merely to turn the selector switch to the required numbers—it takes three different movements to call; the system starts with 721 and runs to 730. I have shown to several of our visitors the time it takes to call a station, which is about 9 seconds.

It is very often necessary for one station to talk to three stations, or four stations at a time and we have what we call a master switch and one station can get every other station on the line by working that mechanism. Mr. McMeen went further to help us in the problem, (but we did not take his further suggestion, not because we did not want it, but because we could not afford it) wherein he offered to give us a signal board which would show, by means of lights when we were calling a series of stations, whether they answered or not. If station C called stations B, E and F, under our present system, station C would ring first station B, then station E and then station F. All the stations have orders to wait on the line until someone talks. Mr. McMeen designed an indicating board that would quickly indicate who was on the line, would show when B was on the line and next E was on the line and next F was on the line. That was very nice but involved some financial difficulties that we did not care to meet. Otherwise, in all matters, it is most satisfactory to us.

S. G. McMeen: I might say that although Mr. Lisberger spoke of this as automatic, it is not an adaptation of the automatic station equipment. It is an adaptation of the railway dispatching apparatus. The devices used are not telephone exchange selectors, but railway telephone selectors, although instead of working the telegraph key, the operator works it with a round, automatic station dial. This is merely used as an interruptor for the calling impulses.

Gregory Brown: Mr. Miller brought up the question of separate signalling circuits. There is one type of selector, so far as I know, that uses three wires—one for signalling and two for talking. That has not been very extensively used. When you consider the impedance of the selectors across the line, it hardly seems necessary to consider that line very heavily loaded as far as transmission is concerned. For that reason, I do not believe it would be necessary to have a separate signalling wire. Selectors are also being experimented with now that have an impedance of something over 600,000 ohms. These selectors contain advantages due to that high resistance, and if they are used, it certainly would not be necessary from a transmission standpoint to have an extra signalling wire.

Mr. Cramer seems to have had quite a few troubles. The first he mentions is that he does not find it feasible to signal and talk at the same time. I have been around pretty nearly all over the country on the various roads, and this is a complaint that is practically new to me. In some cases I have found this to occur, but on investigation we generally find that there is some trouble with the despatchers apparatus. One of the troubles that occurs perhaps more than any other and causes these results is the breaking down of the condensers at the dispatcher's office. These would not round off a sending wave to such a great extent.

The length of ring has been criticized—the length of ring at the station. I have gotten around that, where they want a longer ring, by installing a strap key at the dispatcher's office. This key is wired in a parallel with the automatic keys, and if the dispatcher, for any reason wants the bell in the station he is calling to ring longer than would ordinarily be the case, he turns the calling key of that station, and when he hears the answer back he merely presses down the strap key. There are various other modifications of selector arrangements which permit the bell to ring in the substation until the substation operator presses a button. In fact, most any kind of service can be given, according to what the particular railroad wants, but, as a general thing, most of them are satisfied with a certain length ring, about a second and a half, uniformly in all stations.

Another trouble that was experienced was that the agent sticks a toothpick or something in the push button and holds it down. The obvious plan to pursue there is to fire the agent; and this has been done in a great many cases, especially when the telephone was first used on railroads. As has been mentioned by several of the speakers, the operators bucked a good deal at the introduction of the telephone, their idea being that they probably were going to have their salaries reduced, or some of them would lose their jobs. It is not the policy of large railroads to put men out of employment except in very extreme cases, and if the introduction of the telephone permits offices to be closed, or forces to be reduced at certain points the men as a rule are taken care of in some other position.

A test on a 33,000-volt line was mentioned in which the apparatus of two manufacturers was used. It seems to me that the telephone apparatus used in this test is at least very similar among manufacturers, that is, the large manufacturers, and that it hardly could be a question of quality of apparatus to show up in the way that was indicated; that is, according to the statement that was made, I gather that one of them failed completely, and the other one gave good satisfaction. It seems to me there must have been another factor that entered into those two tests that caused that great difference, because the transmitters and coils, and so on, are very nearly similar insofar as their excellence is concerned.

Mr. Bennett spoke of calling and selecting on transmission lines. Mr. McMeen answered this question about the only way it can be answered, I guess, and that is with proper transpositions of your line if you get a quiet telephone line you can do anything with it in the way of talking and selecting.

Mr. Pope brought up the point in favor of the telegraph in that you could hear the telegraph when you were at some distance away from the instrument, whereas in the telephone you have to have the instrument up to your ear. About two months ago I conducted a trial installation down on one of the Pennsylvania lines, using a new type of loud speaking receiver. Criticism has been made of the telephone when used on a railroad division that it was all right for every purpose except blocking, and that for this purpose it was not as quick as the telegraph, and this criticism seemed to be more or less justified. The reason that this criticism was made was that in telephone blocking it is necessary for the operator to ring up another operator and then go through the motions of putting the receiver on his head and talking with him, whereas with the telegraph he merely ticks off what he wants to say and it is done. And that was the reason for the development or the experiments with loud speakers of various kinds and the attempt to develop a good one.

There has been considerable work done on this, and although it has been comparatively easy to get up a loud speaker for blocking—one that was plenty loud enough—still the articulation was not what it should be. This blocking service represents an ideal condition for loud speakers, because the lines are extremely short and are not loaded, and you can take full advantage of all the energy coming out of the transmitter. This installation was put in in three or four of the towers, and was left in for about ten days. During that time it was used exclusively by the operators for blocking trains, and in fact, they much preferred to use these speakers because the work was easier for them. They were then taken out merely to put them in in a better shape the next time as far as mounting is concerned, making it more convenient for use, and also to employ a busy test by means of a buzzer that had not been taken care of in the first installation. It is intended to use or experiment with this same type of receiver for dispatcher's use, and there will shortly be some trials in that field.

Mr. Elwell spoke of a train dispatching line being in use in Australia in 1902, I think it was. In the first part of my paper I mention two or three instances of the early installation of telephones on a train wire. All these installations used code ringing, and for that reason they were not very successful. There was too much of a load on the dispatcher. I think the first one used in this country was in 1883, which is probably before the one mentioned by Mr. Elwell.

I think there is no doubt that the telephone has proven its case on the railroad and I mention in the paper quite a few advantages of the telephone over the telegraph and I can probably mention quite a few more, and anybody who thinks of the matter can easily see that there is no question but what the telephone does have advantages over the telegraph. Mr. Miller, I believe, raised the point about the distinctness with which the intelligence could be transmitted over the telephone—that is, where train orders, important orders regarding train service in which human life is risked—the distinctness with which they could be heard. Now, in sending out orders, the various railroads have standardized, in their telegraph methods, and they have also adopted practically the same scheme when they shifted over to the telephone. In sending out an order the despatcher rings the various operators and they will come in and then he states a certain number, 31 or 23, or whatever it is, which indicates the type of order he is to give and he starts to give his order and as he gives his order he writes it down himself so as not to give the order faster than the operator can take it down. As the dispatcher writes the order when he comes to the name of a town or any figures whatever, engine numbers or anything similar, or the time, besides speaking it in the ordinary manner, he spells it out. After he has completed giving the order the operators in their turn repeat this back to him and as each operator repeats it back to him the despatcher underlines the word repeated, so if there are three operators repeating the record of the order would be in the desptacher's book—it would have three underlines under each word which was repeated, which would supposedly prove it had been repeated by three operators.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 27, 1911.

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CONTINUITY OF SERVICE IN TRANSMISSION SYSTEMS.

BY MAGNUS T. CRAWFORD

INTRODUCTORY STATEMENT

The object of this paper is to give the results of a number of years of operation of the Snoqualmie Falls Transmission system of the Seattle-Tacoma Power Company and to deduce therefrom practical conclusions as to the effectiveness of the method of operation used. The discussion will be confined entirely to the transmission system, and the possibilities of insuring continuous service by means of auxiliary steam plants will not be considered. Each high-tension system is a problem in itself and must be worked out with respect to its individual features and conditions, such as generating capacity in kilowatts, length of lines, size of wires, ratio of resistance and reactance, line voltage and climatic conditions. It is believed however, that a log of the operating results of a particular system is worthy of record, if the conditions of operation are correctly described.

DESCRIPTIVE DATA

The general features of the system are shown in the accompanying diagram and illustrations.

A good description of the original installation as completed in 1900 may be found in *Engineering News*, December 13, 1900, and the evolution of the transmission line was described in a paper read before the Seattle Section of the A.I.E.E., December 19, 1908, published in the PROCEEDINGS, and in the Journal of Electricity, April 24, 1909. This paper covers only the four years 1907, 1908, 1909 and 1910.

Generator capacity 12000 kw., step-up transformers 15,000 kw. Transmission 30,000 volts three-phase, neutral ungrounded.

Poles. Cedar, average height 40 to 50 feet. (12.19 to 15.24 m.).

Spans. 135 to 160 ft. (41.14 to 48.76 m.) average length; up to 1000 ft. (304.8 m.) at river crossings.

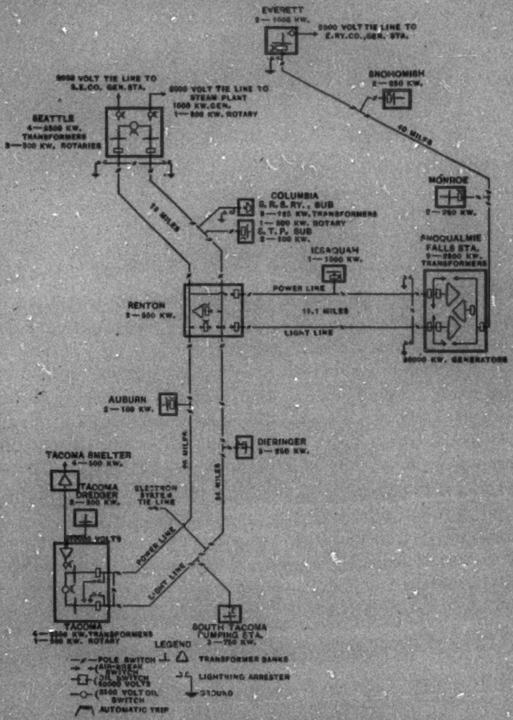

EVERETT
2—1000 KW.
2300 VOLT TIE LINE TO E.RY.CO.,GEN. STA.
SNOHOMISH
2—250 KW.
40 MILES
6600 VOLT TIE LINE TO S.E.CO. GEN. STA.
6600 VOLT TIE LINE TO STEAM PLANT
1000 KW.GEN.
1—500 KW. ROTARY
SEATTLE
4—2500 KW.
TRANSFORMERS
3—500 KW. ROTARIES
13 MILES
COLUMBIA
S. R. & RY., SUB
3—125 KW.TRANSFORMERS
1—300 KW. ROTARY
& T. P. SUB
3—100 KW.
MONROE
2—250 KW.
SNOQUALMIE
FALLS STA.
9—2500 KW.
TRANSFORMERS
ISSAQUAH
1—1000 KW.
POWER LINE
19.1 MILES
LIGHT LINE
RENTON
3—500 KW.
6000 KW. GENERATORS
AUBURN
2—100 KW.
DIERINGER
3—250 KW.
26 MILES
34 MILES
TACOMA SMELTER
4—500 KW.
TACOMA
DREDGER
2—300 KW.
ELECTRON
STATE
TIE LINE
VOLTS
POWER LINE
LIGHT LINE
TACOMA
4—2500 KW.TRANSFORMERS
1—500 KW. ROTARY
SOUTH TACOMA
PUMPING STA.
3—750 KW.
LEGEND
POLE SWITCH
AIR-BREAK SWITCH
OIL SWITCH 60000 VOLTS
2300 VOLT OIL SWITCH
AUTOMATIC TRIP
TRANSFORMER BANKS
LIGHTNING ARRESTER
GROUND

Diagram of 60,000-volt transmission system.

Lines. Falls to Renton 20 miles (32.18 km.) two pole lines. Renton to Seattle 13 miles (20.92 km.), two pole lines. Renton to Tacoma 26 miles (41.84 km.) by one pole line and 34 miles (54.71 km.) by the other. Falls to Everett 40 miles (64.37 km.) one pole line. Tacoma to Smelter at Point Defiance, 6 miles (9.65 km.) one pole line. Total 172 miles (276.8 km.)

Wires. Falls to Renton No. 4/0 seven-strand aluminum. Renton to Seattle and Tacoma, No. 2/0 seven-strand aluminum. Falls to Everett, No. 4 solid copper. Tacoma to Smelter, No. 4 solid copper.

Spacing. 7 by 9 ft. (2.13 by 2.74 m.) and 7 ft. (2.13 m.) equilateral triangles.

Insulators. One piece, tripple petticoat porcelain, 6 in. (15.24 cm.) diameter, Redlands pattern. White imperial porcelain on main lines. Brown porcelain on Everett line, not tested before installation.

Pins. Locust wood, impregnated with paraffine.

Cross Arms. Four by 5¼ in. (10.1 by 11.13 cm.) to 5 by 6 in. (12.7 by 15.24 cm.) select Washington fir.

Switches. At Falls, non-automatic remote control, vertical break oil switches in brick compartments. At Renton, Seattle and Tacoma, non-automatic lever control. rotating horizontal break oil switches in iron tanks. At small stations and for throwing lines in multiple, fused air break "jack" switches or fused horn switches.

Protective Apparatus. Multigap lightning arresters with series resistances.

1908

Wood pins changed to malleable iron on corners and important points

1909

Transmission voltage raised to 60,000 volts on December 6, 1909, using same, wires, poles and cross arms.

Insulators. Four-piece brown porcelain of standard design, each tested to 120,000 volts, and made with threaded 1½-in. (38.1 mm.) pin hole.

Pins. Malleable cast iron with threaded head.

Switches. At Falls and Renton, non-automatic remote control, vertical-break oil switches in steel tanks. At Seattle, Tacoma and Everett, non-automatic lever control rotating horizontal-break oil switches in iron tanks. At small substations, series trip coil actuated automatic overload release, rotating horizontal break oil circuit-breakers in iron tanks.

Disconnecting Switches. Out-door pole top type, three-pole double break, consisting of contact jaws mounted on line insulators with connecting blades rotating in a horizontal plane.

Protective Apparatus. Aluminum cell electrolytic lightning arresters installed at each end of each line.

1910

Additional 8750 kw. generator put in service in November, with 8750 kw. additional step-up transformer capacity.

OUTLINE OF SYSTEM OF OPERATION

In the operation of high-voltage lines on the Snoqualmie system the high-voltage line switches are non-automatic electrically-operated by remote control except those used in throwing the lines in multiple at substations, which are instantaneous overload release switches. The Falls operator has on his switchboard an indicating ammeter and the control handle for an electrically-operated remote-control oil switch for each outgoing high-voltage line.

The generator oil switches are kept blocked in solid on the bus bars except when synchronizing a new machine. If the Snoqualmie system is running in parallel with the Electron system or with other generating systems as is frequently the case, the connection is made with instantaneous overload-release circuit-breakers, and a similar connection is made with the steam plant at Seattle.

When a short circuit comes on the system all automatic circuit breakers connecting other systems and all switches for multiple connections drop out at once, leaving each line separate clear to the Falls. The Falls operator first lowers the voltage and gets the speed of the machinery under control. It is then usually apparent on the line ammeters which line is short circuited, and if it does not burn clear in a few seconds it is opened with the remote-control oil switch. The voltage is then slowly brought back to normal and only a part of the load is lost. The substation operators then open their end of their line at the pole switch, and linemen are sent out to the defective section of the line. This is located by opening all pole switches in the line and then testing out one section at a time, starting at the Falls, until a section is found which shows trouble.

If it is not apparent to the Falls operator which line is in trouble, the short circuit is fed thirty seconds, and one of the lines opened, and if it still does not clear it is fed thirty seconds longer on the other line, and the station is never shut down as long as it can be kept running. Two large water rheostats of iron wire immersed in the tailrace and provided with oil switches are thrown on the generator bus whenever a heavy load is to be dropped, as in opening a short circuited line, and serve to aid the control of speed and voltage. In extreme cases where trouble holds and all lines are opened, the station is run on the water rheostats and each line thrown in again at intervals until one is found that is clear.

Substation operators open all high-tension switches when power goes off the line and immediately make connections with another generating system or steam plant, and pick up the local load until power comes on the lines again.

The details of the system of upkeep employed in connection with the transmission system have been carefully worked out, as a great many of the interruptions in service may be avoided by proper maintenance of the lines. Eight patrolmen are employed and each held responsible for the condition of a part of the line. They are stationed at a transforming station as near as possible to the middle of their patrol, and furnished with a residence and a telephone from the private line. Patrolmen are furnished with a saddle horse and saddle bag containing telephone test set, sundry tools and material, and once each week they carefully inspect their section of the line. All badly broken insulators are replaced and any other necessary repairs made. Every two miles along the line a small booth is fastened to a pole, and a stock of insulators, pins, cross arms, line wire, etc., are kept locked up therein, so that in case of trouble, material for repairs will always be within one mile.

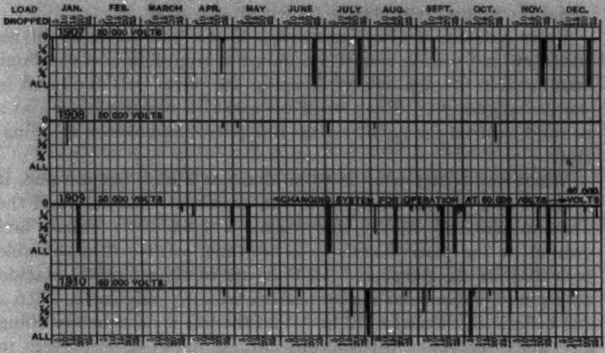
Each patrolman also has charge of the pole switches in his territory and once a month he makes a complete and thorough examination of each switch, keeping the parts well oiled and in perfect alignment. Each week he makes a written report on a printed form of the results of his line patrol and switch examination.

When any repair work is to be done on a high-tension line, it is killed and opened by an air-break switch at each end, and the lineman working on the line makes a solid short circuit and ground at the point where he is working, with a flexible cable provided for the purpose. All lines are in charge of the station operator, and linemen notify the operator by telephone when a line is desired, waiting until he is told the line is dead before doing any work thereon. All communications between employees in connection with high voltage are repeated back to the speaker, and are written down in the station log book. These precautions are necessary to reduce mistakes to a minimum.

EXPLANATION OF TABLES

The following tables and curves show a log of the operation of the transmission system for the last four years. All cases of trouble on the high-tension lines or in transformers that caused an appreciable disturbance of the line voltage are recorded, but short circuits on low-tension distribution systems and other troubles not chargeable to the transmission system are excluded. The times given as " shut down " are cases where power was off the high tension lines of the Snoqualmie system long enough to switch out the defective line. The actual service interruptions were of very short duration, as power was usually obtained immediately from another system or steam plant at Seattle, Tacoma and Everett.

The conditions of transmission are somewhat severe, as the lines pass through rough country and along country roads. The land is being cleared for agricultural purposes and for new railroads, so that a great deal of blasting and grading is being carried on, causing much trouble. The pole line has been built ten years, and has not the mechanical factor of safety of a new line. The tables show how the troubles resulting from these adverse conditions were handled with a minimum disturbance to service, as out of the total of 66 cases of trouble given in the table, 52, or about 80 per cent, were handled without an interruption of service.



Service interruptions on the Snoqualmie transmission system

During the latter part of 1907 considerable trouble was caused by burned wooden pins. These pins had been in service nearly seven years, and the threaded tops were softened to pulp, apparently by the action of nitric acid formed from the air and moisture by the leakage currents.

The line was gone over by patrolmen and on all turns and important places the wood pins were replaced by malleable iron pins, and no more trouble resulted from this cause. With the weak points thus fixed the system gave practically continuous service during the year 1908. During 1909 the work of reconstruction for 60,000 volts was in progress and nearly half of the system was cut out during working hours for work thereon, and the switching was in a temporary condition at many places. These circumstances made it difficult to handle trouble without interruption of service. During the year since the change to 60,000 volts there have been only two shut-downs out of 23 cases of trouble, showing the method of operation is equally successful at the increased voltage.

The duplicate high voltage lines are known by the names light and power lines respectively, and are divided into sections known by the names of the principal stations toward which they lead from the junction point at Renton.

TABLE I

SERVICE INTERRUPTIONS

Date	Extent	Load dropped	Remarks
1907 Jan. 2 9:55 p.m.	Short voltage dip	About half	Snow on outlets at transformer house at Falls makes short circuit on power line by starting an arc. Falls operator opened power line and cleared trouble, throwing on water rheostats until load returned.
Jan. 3 1:10 a.m.	Short voltage dip	None	Short circuit on light line, burned clear. Cause unknown.
April 23 4:15 p.m.	Prolonged voltage dip	Nearly all	Telephone wires blown into high-tension wires near Seattle by high wind. Burned clear.
April 24 6:04 p.m.	Four seconds voltage dip	Small	Short circuit on system, cause unknown. Burned clear.
June 24 2:15 p.m.	Shut down	All	Solid short circuit on both lines holds until lines are opened. Cause unknown. No trouble found when lines are put in again.
July 23 8:30 p.m.	Shut down	All	Piece of iron wire thrown over both lines near Tacoma. Falls operator pulled the short circuit 30 seconds on each line before shutting down, but unable to burn clear.
August 1 7:50 p.m.	Eight seconds voltage dip	One-fourth	Arc started by lightning between wires at outlets in Seattle substation. Burned clear by lowering voltage.
Sept. 5 1:15 p.m.	Dip in voltage	One-fourth	Severe short circuit comes on light line but is burned clear. Cause unknown.

TABLE I—Continued

Date	Extent	Load dropped	Remarks
Sept. 11 12:45 p.m.	Dip in voltage	Nearly half	Lightning storm between Renton and Tacoma. Short circuit appears on both lines but burns itself clear.
Oct. 16 10:00 a.m.	Small voltage dip	Small	Light short circuit on power line is burned clear. Caused by limb from burning tree between Auburn and Tacoma.
1907 Nov. 22 2:45 p.m.	Shut down	All	Wooden insulator pins burned off on corner pole between Renton and Kent causing short circuit and ground on light line. Arcing ground burns up nearly two spans of wire at point of break. Surges burn up multi gap lightning arresters in stations and cause pins to burn off at other points on lines where insulators were defective.
Nov. 23 5-6 p.m.	Frequent successive voltage dips	About half	Trouble develops from burned insulator pins at different points probably at places where insulators were cracked by surging ground of Nov. 22. Pole near Everett was set on fire and Everett line was out until repaired. One wire of light line in Seattle burned off cross arm and came across 13,000-volt lead of S. E. Co. As Seattle power line was cut out for repairs at other points, Seattle was out eight minutes. One transformer punctured at Seattle. Falls line also down from burned off pins near Renton but cut out before causing damage,and repairs made.
Dec. 4 3:30 p.m.	Six second dip	One-fourth	Short circuit appeared on light line and is burned clear. Low tension wires get tangled up on pole in Auburn and one of them swings up over high-tension line and is burned off. Caused by high winds.
Dec. 23 4:00 p.m.	Shut down	All	Heavy wind storm blows limb of tree into light line near Issaquah, blows down power line near Kent and light line near Auburn, all at same time Last two places were where pins were nearly burnt off. Falls operator lowered voltage and stayed in on each line separately for 60 seconds, but was unable to clear trouble. Station ran on water rheostats until troubles were located and one line repaired through,

TABLE I—Continued

Date	Extent	Load dropped	Remarks
1908			
Jan. 12 5:00 p.m.	Voltage dip	About half	Short circuit on branch line to smelter in Tacoma. High-tension fuses in Tacoma substation did not open and short circuit was pulled 30 seconds by Falls operator and burned clear. Cause unknown.
April 24 3:50 a.m.	Ten seconds voltage dip	Small	Tree blown into Falls light line one-half mile (0.8 km.) from Renton. Light line opened and trouble cleared.
April 24 4:20 a.m.	Short voltage dip	Small	Everett line down near Snohomish due to defective insulators. Everett line opened and trouble cleared.
May 2 1:50 p.m.	Short voltage dip	Small	Defective insulators on line to Tacoma lets wires down on cross arm. Cross arm burned off, clearing trouble.
July 2 3:15 p.m.	Ten second voltage dip	One-fourth	Short circuit and ground on power line due to defective pole switch at Seattle. Seattle operator knew location of trouble and cleared it by opening high-tension line oil switch.
August 3 9:45 p.m.	Short voltage dip	Small	500 kw. transformer burned out at Lewis & Wiley' pumping station. Cleared by high-tension fuse in substation.
Oct. 22 4:32 a.m.	Voltage dip	Nearly half	Short circuit on line to dredger in Tacoma harbor cleared by high-tension fuse. Caused by salt water fog where line runs about 30 ft. (9.14 m.) from surface of water, and spacing between wires only 3½ ft. (8.9 cm.)
1909			
Jan. 3 8:10 p.m.	Short voltage dip	Small	Short circuit on Tacoma dredger line. Cleared by high-tension fuses. Caused by salt fog.
Jan. 19 2:30 p.m.	Shut down	All	Line to Tacoma smelter was connected to both light and power lines at Tacoma substation when a land slide carried away several spans. Falls operator lowered voltage and kept each line in 30 seconds before opening.
March 26 5:00 a.m.	Short voltage dip	Small	500-kw. transformer burned out at Lewis & Wiley pumping plant. Cleared by high-tension fuse in substation.
April 4 8:45 p.m.	Long voltage dip	One-fourth	Severe short circuit on Tacoma dredger line holds until voltage is lowered. Probably from salt fog.

TABLE I—Continued

Date	Extent	Load dropped	Remarks
April 29 8:20 a.m.	Voltage dip	Nearly half	Transformer burned out and grounded on Tacoma smelter line. Discharges lightning arresters in Seattle and Tacoma substations.
May 10 11:25 a.m.	Shut down	All	Burning tree falls into Tacoma power line near Auburn, breaking down four spans of line, causing arcing ground that results in puncture of No. 1 generator armature. Lines opened until defective generator could be cut out and load picked up on rest of station.
July 2 5:15 p.m.	Shut down	All	While Tacoma power line was cut out for work thereon, light line was connected to both Falls lines and a tree was blown into the light line near Auburn, making a short circuit and ground which would not burn clear. Both lines had to be opened until defective line could be switched out at Renton.
July 3 12:35 a.m.	Heavy voltage dip	Small	Short circuit on power line burned clear. Linemen repairing break of July 2nd on a dark night left telephone wire across line, and when line is switched in at Renton telephone wire is fused.
July 15 10:30 a.m.	Voltage dip	Half	Short circuit on light line near Seattle, cause unknown. Light line opened, clearing trouble.
August 2 12:15 p.m.	Sixty seconds voltage dip	Over half	Falls line cut out for linemen to work on about 3 miles (4.8 km.) from Renton. A solid short circuit and ground put on wires where they were working with a piece of ¼-in. (6.35 mm.) steel mast arm rope, as a safety precaution. By mistake line was reported clear and switched in at Renton end with short circuit still on and Renton multiple switch closed solid. Falls operator lowered voltage and pulled the short circuit by way of light line and Renton multiple switch. In about 60 seconds the ¼-in. (6.35-mm.) steel rope was fused clear of the line, and water rheostats were thrown on generator bus.
August 16 5:20 p.m.	Shut down	All	Steam shovel gets into line at Seattle, letting down two spans and causing arcing ground and short circuit that punctures two transformers and No. 5 generator at Falls. Station shut down until defective apparatus could be cut out.

TABLE I—Continued

Date	Extent	Load dropped	Remarks
August 26 2:50 p.m.	Short voltage dip	Small	Short circuit in 500-kw. transformer at Lewis & Wiley's pumping plant. Cleared by high-tension fuse in substation.
Sept. 4 2:35 p.m.	Voltage dip	Everett only	Short circuit on Everett line cause unknown. Cleared by high-tension fuse on Everett line.
Sept. 13 12:15 p.m.	Voltage dip	Everett only	Short circuit on Everett line caused by blasting stump into line. Cleared by fuses on Everett line.
Sept. 16 3:20 p.m.	Shut down	All	Seattle light line short circuit and grounded by blasting stumps near Seattle. Arcing ground punctures No. 3 generator armature and station is shut down.
Sept. 24 7:00 p.m.	Shut down	All	Pile driver knocks down long span in Everett line across Snohomish River. Fuses blow on Everett line and start arc across wires short circuiting high tension bus in transformer house at Falls; station shut down until bus could be cleared.
Sept. 26 7:12 p.m.	Voltage dip	Everett only	Short circuit on Everett line cleared by fuses. Pile driver strikes line at Snohomish.
Sept. 27 2:40 p.m.	Voltage dip	Small	Pole switch at Puyallup does not close properly and starts arc across wires when opened. Burned clear by lowering voltage.
Sept. 30 8:05 p.m.	Heavy voltage dip	One-fourth	800-kw. transformer burned out at South Tacoma pumping station. Cleared by fuses in substation.
Oct. 31 10:35 a.m.	Shut down	All	Light line cut out for work thereon when power line was torn down by blasting stumps near Kent. Falls operator was unable to burn the trouble off and cut both lines out until Renton switched clear of the trouble.
Nov. 18 1:30 p.m.	No shut-down of system	Half	Floods and high winds washed out 12 poles carrying both light and power lines near Tacoma, and they were blown over. Trouble reported and lines opened before they went down Wires not broken and poles were pulled up clear of the ground and lines cut in

TABLE I—Continued

Date	Extent	Load dropped	Remarks
Nov. 25 9:00 a.m.	Shut down	All	Flood washes out Everett line near Snohomish. Wires and switching in temporary condition at Falls during change to 60,000 volts, and unable to clear without shut down.
Dec. 5			SYSTEM CHANGED FROM 30,000 TO 60,000 VOLTS WITHOUT INTERRUPTION OF SERVICE.
Dec. 6 10:28 p.m.	Heavy voltage dip	Over half	Limb of tree blown into light line 2½ miles (4 km.) from Falls breaking wires and causing short circuit and arcing ground Electrolytic lightning arresters discharged taking heavy surges off of line. Light line opened by operator clearing trouble; water rheostats thrown on until load returned.
Dec. 20 10:15 a.m.	Voltage dip	Small	Pole switch arced across at Renton when opening Tacoma light line. Switch closed again and dip of voltage breaks arc.
Dec. 27 3:10 p.m.	Heavy voltage dip	One-fourth	Short circuit on Everett line cleared by opening line switch at Falls. Caused by blasting stump into line a few miles from the Falls, breaking wires.
Jan. 25 8:07 p.m.	Voltage dip	Nearly half	Severe short circuit cleared by opening light line. Multiple switches at Seattle and Tacoma drop out. Trouble caused by high wind blowing over a corner pole near Kent, the line falling into a lead of telephone wires. Telephone system damaged but slightly.
April 16 12:25 p.m.	Slight voltage dip and swinging of ground detector	None	Ground appears on system but burns clear in a few seconds. Caused by blasting stumps 300 ft. (91.44 m.) from line near Milton. Large rock breaks one wire of line and it falls to ground burning off clear at Falls end. Trouble located and line cut out and repaired.
April 24 9:05 a.m.	Voltage dip	Small	Pole switch on Tacoma light line arced across at Renton when opening charging current of line with blades set too close. Cleared by openign light line at Falls.

TABLE I—Continued

Date	Extent	Load dropped	Remarks
May 23 8:15 p.m.	Voltage dip	Small	Light short circuit burns clear at once. Tree fell across light line near Renton but did not break wires. Renton operator notified of trouble and opens line at Renton.
June 12 11:35 p.m.	Slight voltage dip	Small	Surge appears on light line and ground detector, clearing immediately. Transformers at South Tacoma pumping station burned out. Trouble cleared by high-tension fuse in substation. This substation owned and operated by consumer.
July 16 9:15 a.m.	Prolonged voltage dip	Over half	Pole switch at Renton arced across when opening charging current of line with blades set too close. Short circuit appears on both lines and Falls operator opened light line. As this did not clear trouble, light line was closed again and power line opened clearing trouble.
July 26 8:10 a.m.	Heavy voltage dip	Half	Short circuit appears on Everett line and is burned clear. Cause unknown.
July 26 9:45 a.m.	Shut down	All	Tree blew across Everett line breaking wires down. Remote control handles for line switches were in a temporary location at one side of switchboard while some new panels were being put into position. Operator made mistake in switching and had to open all lines and throw on rheostats until generators could be controlled.
August 22 1:35 p.m.	Slight voltage dip	Small	Ground appears on light line, discharging electrolytic lightning arresters. Burns itself clear. Cause unknown.
August 26 6:35 p.m.	Slight voltage dip	None	Ground develops and clears itself. Cause unknown.
Sept. 3 11:15 a.m.	Voltage dip	Half	Telephone wires pulled across power line in Seattle by careless lineman. Power line opened by operator and trouble cleared. Half of load dropped as Tacoma was running on power line with light line cut out temporarily.

TABLE I—Continued

Date	Extent	Load dropped	Remarks
Sept. 7 11:05 a.m.	Voltage dip	One-fourth	Short circuit on Everett line from unknown cause. Trouble clears when Everett line is cleared.
Oct. 4 11:25 p.m.	Shut down	All	Corner pole cut down with an axe near Tacoma, both light and power lines falling across county road and telephone lead. Falls operator unable to burn clear and both lines left out until defective section could be opened. Telephone Company's system not damaged severely.
Oct. 5 11:15 a.m.	Voltage dip	Small	Short circuit on light line burns itself clear. Cause unknown.
Oct. 17 3:15 a.m.	Voltage dip	Small	Short circuit cleared by opening Everett line. Stump blasted into line by contractor building new railroad near line.
Oct. 30 11:03 a.m.	Heavy voltage dip	Over half	Short circuit appears on both lines but burns itself clear. Cause unknown.
Nov. 4 5:40 p.m.	Two successive voltage dips	One-fourth	Stump blasted into Everett line. Trouble burned clear.
Nov. 25 8:05 p.m.	Voltage dip	One-fourth	Short circuit appears and is burned clear in a few seconds. Caused by blasting piece of stump into Everett line.
Dec. 5 7:00 p.m.	Three severe voltage dips	Half	Malicious persons, throw piece of half-inch (12.7 mm.) steel cable over both light and power lines about three miles (4.82 km.) from Renton on Seattle lines. Steel cable was burned in two and trouble cleared on power line although line wires were badly scarred. On light line one line wire was burned in two, fell to ground and burned off clear of ground on Falls side. Falls operator did not open any lines, as short circuit appeared the same on each and was burned clear.
Dec. 11 12:15 a.m.	Voltage dip	Small	Defective insulator on pole switch at Seattle punctures and starts arc to ground. Electrolytic lightning arresters flash over, taking surge to ground and trouble burns itself clear.

TABLE II

SUMMARY OF SERVICE INTERRUPTIONS 1907-8-9-10

	Shut downs	Voltage dips		Total cases
		Dropping half load	Dropping one-fourth load	
1. Defective line construction, failure of switches, insulators, etc......	1	2	7	10
2. Failure in transformers...........	0	1	5	6
3. Malicious interference, blasting stumps, etc....................	6	1	7	14
4. Winds, fires, floods, fogs, etc......	6	6	6	18
5. Lightning........................	0	1	1	2
6. Mistakes by employees...........	0	2	1	3
7. Unknown........................	1	4	8	13
Totals.....................	14	17	35	66

NOTE.—Of the fourteen cases of shut down, seven occurred during the half of 1909 when the system was running on one line during working hours to permit reconstruction for 60,000 volts. During the other 3½ years the average was two cases of shut down per year.

DISCUSSION OF RESULTS

Before discussing the above results, a definition of continuous service is necessary. In cases where only a voltage dip is shown, the bus voltage of 115 volts dipped down to some value between 40 and 90 volts for a few seconds and then returned to normal. To the lighting consumer this is not objectionable if it does not occur too frequently. To the small power consumer, such as shops and industries using motors in small units, generally speaking it is not a serious inconvenience, as the motors will often come back up to speed and will at most only require restarting. In the case of very large power units, they will usually stay in on the line unless they are heavily loaded or the dip is too prolonged.

The 500-kw. synchronous converters on the system almost always stay in and are not cut off until the current goes clear off the line. On the other hand if the voltage dip is very sudden in its return to normal, as where a short circuit is opened at its maximum and a Tirrill regulator has held up the generator voltage, large synchronous machines are much more apt to be thrown out. In the above table there are 52 cases where the voltage dipped but the system was not shut down, and in only 17 of these cases was the dip sufficiently prolonged to lose any considerable amount of load. In the other cases practically all the large motors stayed on the line. It seems reasonable then to conclude that moderate voltage dips of short duration do not constitute an interruption worth considering.

In cases where the voltage gets to a very low value and does not return to normal for ten seconds or more, the most of the power load will be dropped, but the lighting load will be returned. The power consumer is then put to the inconvenience of stopping work long enough to start up his motors again. The railway station operator must synchronize his converting units again, but if the drip is not over thirty seconds they should still have considerable speed and this should only be a few minutes work, which is not a hardship to railway service. Some power installations will suffer great inconvenience, such as for instance an ammonia compressing outfit, and also some electrolytic processes, where even a momentary shut down will cause heavy loss. However, such consumers will only form a small percentage of the average power company's business, and any expensive equipment to insure them absolutely continuous service should be a part of their own installation.

Porcelain insulator and iron pin used on 30,000-volt line

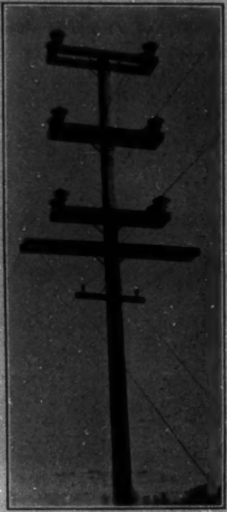
In cases where power goes completely off, all load is dropped and all consumers suffer maximum of inconvenience until service is resumed. The gross income of the power company practically ceases and the operating expenses continue, besides the loss in good will which can not be measured. If service is resumed within five minutes, the average consumer will not suffer serious loss, but where the shut down extends over thirty minutes or an hour the financial loss and inconvenience is very considerable to all parties concerned. We may then conclude that prolonged voltage dips are an inconvenience but if of infrequent occurrence are not serious menaces to satisfactory service, whereas complete shut-downs cause heavy loss. Speaking from the average consumers viewpoint, commercially continuous service may include infrequent voltage dips and very rare shut-downs of periods never exceeding five minutes.

Causes of Troubles. The first two causes in Table II are defective construction and apparatus, and burn-outs of machinery. By testing all line insulators for a voltage a little over twice normal and carefully testing all machinery winding before installation the entire system may be made to withstand double normal voltage for several minutes without failure of insulation. This means that transient voltages considerably in excess of double normal voltage can be withstood, as brought out by Steinmetz and Hayden in a paper before the A.I.E.E. in June, 1910. By installing protective apparatus such as air relief gaps which are set to break down at double voltage and which have a time lag much lower than that of the insulation of the

30,000-volt entrance construction

system, practically all destructive surges can be taken off the system. This may be done by installing electrolytic lightning arresters at the entrance to all important stations. If lightning becomes so troublesome as to shatter insulators on the line where it strikes at some distance from an arrester, relief gaps may be installed at each insulator if necessary, by means of arcing rings as described by Nicholson in a paper before the A.I.E.E., March 30, 1910. In this plant, however, lightning strokes on the line are very rare, and by using wood poles and cross arms, an entire pole may be burned down without interrupting service if the wires are not broken. The first two causes of trouble and also the sixth can thus be reduced to a minimum by properly testing the insulation of apparatus and the installation of protective apparatus.

Pole-top construction at square turns. (60,000 volts)



Pole-top construction where two lines are on the same pole, showing guard wires over railroad. (60,000 volts)

Blasting stumps is a source of much annoyance in this section of the country, and can best be handled by a campaign of publicity. The patrolman on each section of the line should make it his business to become personally acquainted with all the ranchers enroute and keep his eye open for all evidences of preparation for clearing land, and when he sees blasting is to be done call attention to the notices of warning kept on each pole, and show every desire to coöperate with the parties concerned and have the line killed before blasting is done. Deliberate interference should be prosecuted vigorously by arrest and fine where possible.

Pole-top construction on main lines. (60,000 volts)

Entrance tubes at substations. (60,000 volts)

Troubles from winds, fires, floods, etc., can be mitigated by using a very large factor of safety in the mechanical construction of the line, and by putting the high tension wires at a good height above all telephone and other wires easily broken. Structures in soft soil should be set solidly in rock boxes and well braced, lines taken via separate routes whenever possible, and always on separate pole lines. All large trees that can blow into the line should be bought and cut down, and the brush kept closely cut on the right of way.

Mistakes of employees can be reduced by providing them with definite written instructions on their duties and course of action under various conditions and by providing them with the best working equipment. Station operators in a plant employing non-automatic operation are very important units in the system; a little welfare work and good pay to good men, and in fact anything that will make them take interest in their work and pride in good results will prove an excellent investment.

Results of Method of Operation. The standard practice in the operation of duplicate transmission lines is to install automatic overload relays and circuit breakers on each line at the generating station, and reverse current relays with automatic circuit breakers at the substation. Even with complicated systems this idea may be carried out so that theoretically a short circuit anywhere on the system will automatically be cleared and the defective line cut out. The experience of this company has

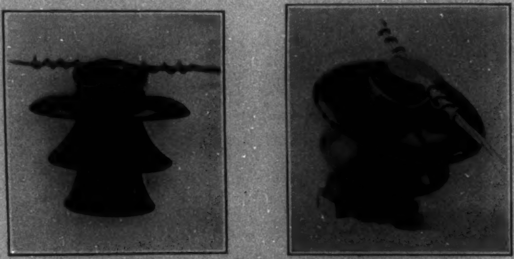
Malleable cast iron pins. Cross-arm pin fits 1¾-in. hole in old crossarms. T-headed bolt slips into a seat on a shoulder cast on inside of shank at bottom, and is tightened up under cross-arm. Weights 3¾ and 7 lb. Ultimate strength 1800 lb. at line wire. (60,000 volts)

Standard pole switch. (60,000 volts)

been that practically better results can be obtained by placing the control of the high-tension lines in the hands of a carefully trained operator. From the operation of this system it is believed that the non-automatic method of operation is less apt to produce destructive oscillations when a short circuit is being cleared from the system. Taking for instance a case where a piece of iron wire is thrown across the line. There being no automatic regulation except slowly acting water wheel governors, the speed and voltage of the generating units dip severely. The operator encourages this and blocks the action of the governors, feeding the short circuit at the reduced voltage. The low-frequency high-power surge first set up by the short circuit may thus be reduced in intensity, being also dissipated by the resistance and cushioned by the reactance of the line, and the station is then simply running on a severe overload for a few seconds. If it is apparent which line is short circuited, it may then be opened with safety. If on the other hand the voltage and speed are automatically held up as far as possible by Tirrill regulators and governors, and the surge is ruptured at a point other than zero in the wave, a destructive potential will result which may cause damage.

Switching and lightning arresters at Snoqualmie Falls

In the case of an arcing ground a more severe condition exists than in a short circuit, as in cases where one line wire is whipping around on the ground, making and breaking contact. In this system where the neutral is ungrounded severely unbalanced strains may be produced in this way, as is shown by the puncturing of generator and transformer windings in such cases. An arcing ground was not always visible on the line ammeter, and an electrostatic ground detector was installed on the generating bus. This indicates promptly all high-tension grounds, and the telephone circuit along the same poles is an instantaneous indicator showing which line is grounded. Grounded lines are cut out without attempting to burn clear, and the installation of electrolytic arresters on the lines, transformers with reinforced insulation on the end coils and static relief gaps on the generating bus bars has given entire freedom from trouble from arcing grounds, as shown by the absence of failures of insulation since the installation of the new equipment in 1909.



Showing type of tie used and 60,000-volt insulator. 4/0 seven-strand aluminum cable with No. 2 tie wire

Since the change to 60,000 volts it has been the practice to open the defective line if it does not burn clear in about five to eight seconds instead of holding for thirty seconds. By the installation of a Tirrill regulator with a special relay for lowering the voltage during a short circuit the operator does not have to look after the voltage, and with accurately reading deadbeat line ammeters he is able to see the situation inside of five seconds. This equipment has been recently installed. The switches for multiple connections now installed on the low-tension side at substations work instantly instead of in the slow uncertain manner of the old 30,000-volt fuses used for this purpose, so that much better performance can be expected in handling short circuits in the future.

This method of operation is applicable to a system of several generating stations, by giving each generating station a certain amount of transmission system, and then using instantaneous automatic circuit breakers at the point of connection. These circuit breakers can be set to carry the full value of interchange current so that the plants can be operated in parallel and with any desired sharing of load; but when a short circuit comes on the line, that line and its generating station will immediately be separated from the rest of the system and can clear its own trouble. Mr. Downing's paper before the San Francisco meeting in May, 1910 on the " High Tension Network of a General Power System " describes a system operated in this way.

It is apparent from this paper that there are a number of features which an engineer could employ in building a new line that would prevent many interruptions, such as stringing the lines at a greater height and supporting them on strong structures along private right-of-way, to avoid interference. The desirability of continuous service depends on the character of the power business served, and a balance may be struck at a point where further investment to secure greater reliability may not be warranted.

DISCUSSION ON "CONTINUITY OF SERVICE IN TRANSMISSION SYSTEMS." LOS ANGELES, CAL., APRIL 27, 1911.

R. J. C. Wood: The first thing that attracted my attention was that the substation in which the line ended was solidly connected. It might be that interruptions could be made still shorter if each substation could be connected onto either end of the light or power lines, unless of course, the steam plants which the author mentions as being on the other end of the line, are kept in operation at all times, ready to pick up the load.

It is stated that an open short circuit taking place on the line is opened in a few seconds if it does not clear itself. This would seem to allow the possibility of burning the line in two. The more general practice, I believe, among the companies here is to drop the voltage as soon as possible and clear the short circuit.

It would also seem that the method of cutting in on the line every 30 sec. might be very severe on the generators and transformers.

With reference to the number of patrolmen, it states there are eight patrolmen and there are 106 miles of territory covered. That is not counting the lines twice over, for there is a double length of about 164 miles. I would like to ask the author if each man works by himself or both together. If each man works by himself it would mean he only had about 20 miles to look after.

There are several references in the latter portion of the paper in regard to electrolytic lightning arresters, and it would be interesting to know if they have met with universal success.

Reverting to the matter of testing lines to find out which section is in trouble, I would like to know whether the author plugs the line right in on the bus, or whether he separates the generator bus and then tests the thing out easily, bringing it up from a local tension.

I didn't notice any reference to the size of insulators. They look to me like 14-in. insulators.

P. M. Downing: It is very gratifying to have a paper of this kind presented and have someone come forward with data giving the number of interruptions that have occurred on a system of this kind to be honest enough to give the cause of the interruptions.

I note in the data given that but few, if any of the failures, are attributed to poles or crossarms burning as a result of leakage over the insulators. I infer that a majority of these failures are the result of lightning discharges or from high voltage disturbances. Whether or not any part of them could have been prevented by the use of electrolytic lightning arresters is a matter of conjecture. To one having to do with the operation of long high voltage lines this arrester is a very interesting piece of apparatus. On the system with which I am connected we have never installed any of them on the high voltage lines, their use being limited to the low voltage cable systems. Some transmission companies have installed them but from all of the data that is available they seem to be still in the experimental stage. My own personal experience with arresters is somewhat limited. In the central part of California the only type used is the horn type, their installation generally being limited to the generating important switching centers. Lightning itself strikes the lines occasionally but the result is seldom serious. It may strike the line between poles and burn one or more wires entirely off without effecting in any way the insulators, pins or poles adjacent to where it would strike. During the past winter we had two occurrences of this kind where it struck the line and burned off two wires in each instance. In neither case were the insulators damaged and we would probably not have known what caused the trouble had we not found where the lightning had gone to earth through several poles near where the trouble occurred. This would bear out the truth of the theory that disturbances of this kind were local in character and the high voltage would not extend any distance over the line. This being the case, there is a question in my mind as to whether or not any type of arresters unless located at a great many points along the line will entirely eliminate the troubles due to high voltage conditions of this kind which are known to come up occasionally.

I note that comparatively a few automatic switching devices are used but that fuses are substituted at the substations.

A fuse is all right in its proper place. It will work satisfactorily on small transformer installations but for the larger sizes you need something more substantial than a fuse. At one time it was common practice to use fuses on transformer installations up to 3000 kw. but these are being rapidly superseded by automatic oil switches.

There is one piece of apparatus which the manufacturers have not made as great progress in the development of as they have in other lines of apparatus. I refer to the reverse current relay. There are several types of apparatus of this kind on the market but in almost every instance they become inoperative when the voltage drops below a certain point. Where you have a network fed from a number of different points interconnected in a great many different ways you want something that will automatically cut out a line on which there is trouble before the entire network is effected. Having two long parallel lines tied together at both ends trouble might occur on either line which would make it desirable to cut out the defective line at the receiving end leaving load on the good line. If the lines are long and trouble serious the voltage at the receiving end will very often drop so low that the reverse current relays will not operate. The result of this failure to operate is too often a complete momentary shutdown until the switching is done by hand control.

The simplest and perhaps as reliable a reverse current indicator as can be had is the ordinary induction wattmeter. I have used these to fairly good advantage both to determine the location of trouble and also as reverse current relays for cutting out defective lines.

E. F. Scattergood: I agree with the writer of the paper in recommending that generating stations be tied solidly to the transmission lines and that there be no automatic devices employed. As Mr. Wood has suggested, I believe such is the general practice in this section of the country at least. The objection to the automatic devices, so far as they have been developed, except, I believe, in the cases of branch lines, which are in the nature of feeders and represent only a small load, making any reverse current impossible, are greater than the advantages, because when one of these automatic devices goes out it often happens that others follow, thereby causing a great deal more trouble than originally existed and a great deal more delay and lack of continuity of service.

By way of illustration we may form a mind picture of several 30,000 volt feeders with automatic devices leading from a substation containing a bank of transformers connected to a much higher voltage transmission line by means of another automatic breaker. It has happened even in such a case that the operation of a feeder breaker caused the higher voltage automatic to open also, thus throwing off considerable load and causing similar breakers to go out elsewhere. It would be much better to run some risk of the transformers than to run the risk of the system as a whole being disturbed in that manner unnecessarily.

Mr. Wood, in his paper, very aptly suggested that probably, as the networks become more complicated, it will be desirable to operate with divisions entirely separated but arranged for paralleling at any time.

G. H. Stockbridge: There are a few things that I would like to call attention to, one in particular being the subject of running the two lines parallel through automatic switches in substations. I would like to ask if any experiments have been made along the line of paralleling at the generating station, say a certain number of transformers on one side and a certain number on the other side, to be separated in case of interruption, thus confining the interruption to one-half the load. We have been considering trying this, but there were some complications raised. I would like to know if it has been tried in this case. I notice the statement, " the details of the system of upkeep employed in connection with the transmission system have been carefully worked out as a great many of the interruptions in service may be avoided by proper maintenance of the lines." This is a broad statement. What would apply in one district would be entirely insufficient in another. For example, we find occasional inspection of the insulators is necessary. Possibly it might require a complete inspection annually of our main transmission lines to insure us from interruption.

I also note that it is provided that when the patrolman working on the line makes his inspection that the lineman makes a solid connection to the ground with a cable. This belongs, of course, to the part of the system where the circuits are on separate lines. With the Edison Company in California, where the two lines are run on the same poles, we find it is essential for the man working on the poles to ground both ends of the circuit.

This table of service interruptions is, as I said before, particularly interesting to the operating engineer, showing as it does the causes of the various interruptions and I am surprised to find the causes are relatively few as compared to what they are in Southern California. In fact, I think in Southern California we have almost everything from balloons to birds on poles, including shepherds who leave their flocks long enough to climb a pole and try to magnetize their knives on a 60,000 volt wire.

The porcelain insulator shown in the paper is familiar to our Southern California engineers as being the old type of insulator used on the 30,000 volt line running from San Antonio Canyon into Los Angeles. When they were first installed we had very little trouble but when the load increased, when we had to use both circuits, there was considerable trouble from pole burning, similar to what Mr. Downing has experienced on his lines. This was eliminated to a large extent by taking a piece of galvanized iron and putting it on the top of the bottom crossarm to provide a conductor between the two arms for the leakage current. We found practically all the fires were caused by leaking across the gap between the top and bottom arm and by providing a channel for this we had but little trouble.

I am interested in the apparatus for taking care of lightning and so forth by air gaps. Our experience with air gaps in this country is not very satisfactory. We found the discharge point varied so much with the condition of the atmosphere. A gap which would be pressure-safe in dry weather would discharge more in foggy weather or a heavy mist. Perhaps there is some way of eliminating this besides installing electrolytic lightning arresters in series with them. If that is so, we would be interested in knowing what it is.

R. W. Van Noorden: Professor Cory gave us a little outline of what was called the psychological side of the telephone business. In other words, he wanted to show that the working of different systems was not altogether dependent upon the inventions and improvements that had been made. There is some question as to whether one system is an improvement over the other or not. In working our power plants, we have a psychological element, it is not like the one Professor Cory spoke about but is more material. I don't suppose there are any two power plants that are exactly alike. There are no two power plants that have exactly the same conditions under which they must operate, and yet there is a great similarity between all plants, let us say, of a certain size. In comparing the working of the Snoqualamie Company and those of California companies, there are many similar problems, but in order to understand these the engineer must understand a great many solutions which he does not learn when buying his machinery, or installing it, or of which the designing engineer may know nothing. I have seen in many cases, where a plant is started for instance and has been running for a year or two, there are changes made, and the engineer will say, "This has cost us more than if we had it in the first place," or "If this thing had been built in such and such a way it would have operated better." Now, the designing engineer did not know that. Possibly he could not have forseen it, but he should have, and as we go along in the science of this work we are learning these things and learning them from the operating end. The point I want to bring out is this, that this paper instead of being simply a description of what a plant has done day by day is really of the utmost importance in helping us to decide what we must provide for in our new developments, and it is just as Mr. Downing said, if the operating engineers would only have nerve enough or be permitted, to come out and give records of this sort, it would do more good to the engineering world than almost anything else that we could get. I am sure I have read this paper with the greatest of pleasure, and while there are many points that come up for discussion among engineers there are points that settle moot questions, questions of theory.

For instance, at one place the author states that if he did not have a Tirrill regulator which held up the voltage he would have had much less trouble in momentary interruptions with synchronous machines. That immediately brings up the subject of the old question between automatic and the non-automatic—I am not referring now to telephone operation, I am referring to power house work. Our experiences on the Pacific Coast have gone to show that the non-automatic workings have been successful where automatic apparatus might not have been, and that is where the question of personality and the psychological study that the engineer has to make comes in. I wish we would have a few more of these papers and that the engineers would consider them of more importance than they do for discussion.

C. O. Poole: There are several features in the system that have brought out points upon which I have debated in my own mind for some time past. One of them is the segregation of multiple circuits by automatic switches. Personally, I have been very much inclined to Mr. Scattergood's views that a good non-automatic was very much better than a poor automatic. Our practice I refer more particularly to southern Nevada—has been to install automatic oil circuit breakers on branch lines and also to protect substation devices. We have found in our experience that a well adjusted, well constructed automatic oil circuit breaker in protecting substations on the high-tension, lines is more reliable than on the low tension. We have found it to work very satisfactorily. I have hesitated however to install automatic switches on the main transmission lines. I can understand, of course, that it may work successfully under Mr. Crawford's conditions. As I remember it, his lines are exceedingly short, and consequently the charge and reaction effects are not so great as on the 200-mile lines. I would like to ask if Mr. Crawford knows of such experience with those lines and if the circuit breakers have dropped out by the line reactions or capacity reactions after the short circuit has occurred. I notice that they use a large rheostat in the tail race for throwing on the circuit before the machine has fallen out of step. I would like to ask if this is one rheostat that is on the bus or a separate rheostat for the separate generators. We had some experience in this line. We installed a new plant and our governors were not put in operation soon enough and we had to control 300,000-kw. by hand, and when a short circuit occurred on the system we had an arrangement made whereby we could throw it over on the rheostat simply to hold the speed of the generator down, and I might add perhaps down to a very low degree, and it worked satisfactorily as long as the wires did not burn out in the tail race.

I note also in Mr. Crawford's paper he states they test the line by, I presume throwing it onto the bus system at the voltage. I would like to ask if he tests it before he closes the line. Also what type of ammeters he uses on the high tension side to indicate the currents.

Ralph Bennett: It has been suggested that we ought to do all switching on the high-tension side. Our system is a 100,000-volt system, delta connected, and we stopped that. We found that every time we switched the load on the high-tension side we got surges that were too great to stand. The insulation breaks down. Some of our transformers are 10,000 kw. and it takes days to get them back into service.

We have installed at each end of our line electrolytic lightning arresters and our voltage rise on loss of load is sufficient to discharge the arresters. We have set the horn gaps back until they are practically non-operative.

We have had in over two years of about 100,000 volts operation so little line trouble that we can say we have had none due to the voltage. We have had a good many bushings broken down and things of that kind but the use of 100,000 volts does not seem so very difficult to us. There is no corona.

Our interruptions are so mixed up with the interruptions of different customers that we hardly know which are ours. Perhaps when we have been operating another year we will be able to say that this, that or the other interruption is due entirely to our own trouble and due to a preventable cause. We cannot say so today.

D. D. Morgan: The Pacific Light & Power Corporation has no circuit breakers at the generating stations; everything is tied in solid. We use some of them on the feeder lines and they work very well. They have worked very well in separating the railroad service from the commercial service.

Our experience with electrolytic lightning-arresters has not been very great. We do not believe that they have done much good in regard to lightning. We have had quite a bit of trouble with our insulators breaking down and shattering on our Kern River system. It seems to be very hard to explain why in a great many instances.

W. B. Gump: I will mention a few points relative to the figures previously quoted as to the limiting quantity of power to be feasibly carried over a single transmission line. Considering first the one extreme, a small amount of power, say, 1000 kw., to be delivered at a point 150 miles distant from the generating plant, we find at once that the capital outlay in transmission is almost certain to be prohibitive. In other words: it is evidently far cheaper to install a steam or gas power plant at the point of delivery.

Taking now the other extreme, a 20,000 or a 30,000-kw. load to be delivered the same distance (150 miles), we certainly have to consider continuity of service. Therefore, the dependence which would be placed on one three-phase line under these conditions necessarily involves a large degree of uncertainty.

Stating the proposition in another way: How much can we afford to pay to insure the transmission system against interruption? Or, putting it in still another way: What portion of the total power generated can we afford to have out of commission for a more or less uncertain period of time?

M. T. Crawford: I will endeavor to reply briefly to all the questions. It is true that with our present arrangement we drop half our load at the main substations if one line goes out, but only for a few seconds, as the switchboard operators first act is to switch this load to the live bus without delay. This we have found to be a more positive and reliable way than to employ reverse current relays. These operators display excellent judgment and while their action is deliberate, it is positive. I remember one case several years ago when power went entirely off of one line, and on the other line only one phase was alive. The voltage dip was not severe enough to stall the two 500-kw. rotary converters, and they were kept in running on one phase, by pulling off all the direct current load. By doing this the operator kept current on the polyphase low-tension lines and carried the more important polyphase feeders for about fifteen minutes, with only single phase high tension supply, as the converters were generating for the dead phases. By that time service was again resumed over another line. I don't know of any automatic equipment that can do work like that.

As to multiplying lines—we have tried multiple connections at both ends and at the middle, but experience has been in favor of connection at the ends only, as we have more reliable operators and equipment at these places.

In regard to testing out lines. It is rare that we have to do this directly. If normal service can be maintained with the good line, the chief operator proceeds with some care in locating the trouble. In many cases farmers or others telephone in and report the location of trouble, as the fireworks display is something to remember especially at night. The telephone system is in duplicate on line, on each pole line, and the telephone wires are almost invariably burned in two at the point of trouble. Hence the section showing telephone trouble is nearly always the one having high tension trouble. This section is left open and the rest of the line thrown in, section at a time, at the pole switch, the oil switch at the generating station being set for instantaneous overload release at a light current value. These switches are completely equipped as automatic circuit breakers for this purpose, and the automatic trip kept cut out during normal operation.

The water rheostat referred to is one large unit provided with an oil switch and panel the same as a feeder, and is thrown directly on the bus. Iron wire coils give good results, and I have also made excellent rheostats out of sheet iron. An iron ribbon 2 in. wide by 0.018 in. thick will carry 2000 amperes continuously if supplied with cooling water. It must be in one continuous strip (made by cutting a sheet zig zag) and well supported mechanically.

Our electrolytic lightning arresters have given us fair service on the whole, and we have two makes. They will take line surges from switching and other causes, although when the surge is repeated several times in succession we have had it burn a path right through the trays to ground.

We have only few expulsion type fuses at small stations, and prefer a series trip oil circuit breaker. Our switch experience has been that the additional cost of a more substantial mechanical construction is worth while. We are rebuilding all our pole switches, making them on the same general lines but of very much more substantial mechanical construction.

The failures of insulators were practically confined to the Everett line when it was equipped with 30,000-volt insulators which were not tested before acceptance, and then usually when a high voltage occurred from some other cause. The new insulators were individually tested by our representative at the factory before acceptance, testing each shell for its share and then the assembled insulator at a rain test of 120,000 volts for five minutes. They measure 14 in. in diameter at the large petticoat.

The patrolmen have each a separate section of line, the maximum single patrol being 20 miles. They are stationed at the middle of their territory, and in such a way that available linemen are only 10 miles apart.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 27, 1911.

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ELECTRICITY IN THE LUMBER INDUSTRY

BY EDWARD J. BARRY

The adoption of electricity for power in the lumber industry of the Northwest is of comparatively recent date although conditions are peculiarly favorable to its use. In the greater number of instances power can be generated locally at a very cheap rate by utilizing the waste products as fuel. These waste products have, so far, little commercial value and in the past any fuel in excess of the quantity required for the steam units and auxiliary machinery has been conveyed to a burner and destroyed. Saw mills, as a rule, are located in remote and sparsely settled districts where the problem of transportation to markets where the by-products of sawdust, shavings and inferior slab wood could be used, makes it scarcely worth while.

The generation of electricity for power offers a method of conserving this wasted energy by opening up a wide field for its application to the many demands for power outside of the sawmill itself. A brief record of the use of electricity in the mills of the Potlatch Lumber Company at Potlatch and Elk River, Idaho, illustrates these conditions. The Potlatch mill with a daily capacity of 750,000 feet, is one of the largest in the West and the power demand increased beyond the capacity of the steam units which consist of a 1500-h.p. corliss engine, belt-connected to line shafting, for the sawmill, and one 1100-h.p. corliss engine for the planing mill.

A year ago one 800-kw. low-pressure, 2200-volt, three-phase, 60-cycle turbine generator was added to operate on the exhaust of the 1500 h.p. engine and has increased the available horse-power output by 60 per cent.

The turbine can also be operated on live steam if necessary in the event of a shut-down of the corliss engine.

The output of this 800-kw. set is used to drive the machinery in the box factory, a 300-h.p. motor driving the blower on the shavings conveyor; it supplies power for the machine shop, car shop and pump house; lights the mills and town at night, and during the summer months supplies 200 h.p. to a local brick-making plant. No increase in boiler capacity has been required and operating conditions are such as to occasion very little extra expense in the way of attention. Storage battery locomotives are employed to handle the lumber from saw-mill to dry-kiln and from dry-kiln to planing mill. These locomotives are seven tons in weight, including battery, and have a start-draw-bar pull of 3,600 lb. (1632 kg.) and a running draw-bar pull of 1500 lb. (680 kg.) at four miles (6.4 km.) per hour. Two 40-kw. belt-driven units are installed for charging the six locomotives employed. Four spare batteries are kept in reserve and can be placed in position on the locomotives in a few minutes in the event of a battery failing.

Snow has given considerable trouble in former years through blocking the tracks and this winter there was designed and put into service an electrically-driven snow brush which has proven eminently successful. The brush consists of a wooden cylinder with rattan canes projecting 16 in. (40.6 cm.) from its surface. This cylinder is driven by a chain geared to a 15-h.p. compound-wound motor mounted on the forward part of a lumber car, the battery for driving it being in the rear. After a heavy fall of snow this rotary plow is sent over the tracks clearing them completely and allowing work to proceed without interruption. Lead batteries are at present in use on the locomotives but nickel-iron batteries have been ordered and it is intended to change over to this type as circumstances permit.

When it was decided to adopt electric drive for the Elk River mill, at present under construction, a complete test was made to determine the horse power required to drive the different machines in the mills.

The machines under test were disconnected from the line-shafting and belt-connected to a motor of the estimated horse power. Wattmeter readings were taken over a period of ten hours on normal load and from this data the necessary information was obtained.

The band mills were found to take from 30 h.p. at no load to as high as 275 h.p. on full load, and it was decided to install 200-h.p. wound-secondary motors for use at Elk River. There are three motors of this type.

The edgers have 75- and 50-h.p. squirrel cage motors, respectively.

The planers in the planing mill are driven by 75-h.p. motors. In cases where it was considered desirable, liberal use has been made of wound-secondary motors.

The power equipment at Elk River consists of one 800-kw., 600-volt, three-phase, 60-cycle turbo-generator and one 500-kw., turbo-generator. A switchboard of eleven panels installed in the turbine room, controls power and lighting feeders to the different departments. For lighting the town and outlying districts the voltage is stepped up to 2,200 volts, with 2200–220–100–volt step-down transformers at centers of distribution.

A 50-kw., 600-220-100-volt transformer is used for sawmill lighting, and in the event of a burn-out provision has been made at the switchboard for connection to the steam exciter set, which can be switched over for this work alone. The 25-kw. motor-generator exciter set can then be used for both generators.

A 50-lamp regulating transformer is used for the series arc system on the log pond and for street lighting in town. The sawmill is intended to run nightly thus making the question of lighting one of importance. This is especially so in lumber grading which calls for powerful, evenly distributed light, with an absence of shadows. Experiments made at Potlatch have convinced us that tungsten clusters and single drop lights give the best effects and in the end cost least for maintenance. Arc lamps inside the mill have been discarded entirely. In the filing room, the saw sharpeners and stretchers are driven by individual motors of two and three h.p. and the small forge has a motor-driven blower. The entire system, both power and lighting, is installed in conduit, reducing the fire risk to a minimum.

Electricity will be used on the log pond for dredging, as the pond bed has a tendency to slit up and impede the passage of logs to the conveyor.

It is intended to use a rotary cutter directly in front of the intake of a powerful pump and convey refuse to the shore over pontoons supporting the pipe line. The pump and cutter will operate from a barge to which the supply wires to the transformer will be attached. The voltage will be stepped down from 2200 to 440 volts at the motors, and three cable drums will pay out or haul in the wire according to the location of the dredge. It has been decided that a 35-h.p. motor will be required for the pump and a 25-h.p. motor for the cutter. If necessary a small motor may be installed for raising or lowering the arm supporting the intake pipe and cutter.

As soon as weather conditions permit the Potlatch Lumber Company intends to experiment with electric drive on the logging machines in the woods, with the view of superseding the steam donkey engines at present in use. There are many drawbacks to the use of steam engines, not the least of these being the ever present risk of fire from cinders and sparks. Every care is taken to minimize this risk but the wholesale devastation in the forests of Idaho, Washington and Oregon last summer has naturally turned the attention of lumber companies operating in the fire areas, towards any method which offers even a partial solution of this difficulty. Water for the boilers must be hauled wherever the donkey engines are located as it is useless to depend on getting it locally except in the rare instances where a stream is within reach. Fuel has to be cut down and sawn into the proper lengths, creating a considerable labor item. A watchman has to be on duty every night during the winter to keep the water from freezing, an occurrence more frequent than desirable, when it comes to starting up in the morning.

Electric logging presents one or two new features in transmission work, the chief difficulty being that the location of the consuming end of the line must, of necessity, change constantly. The transmission line must be guarded against the danger of falling trees, but as it will be always in the rear of logging operations it will be possible to follow the track over logged off land, reducing the risk to a possible interruption, in hilly country, through a tree rolling down from higher ground. When a section has been logged over and a permanent change has to be made in the direction of the transmission line it would appear that a saving could be effected by installing light lattice work steel towers in the first instance. The towers could be set down and guyed to convenient stumps. The line would parallel the logging railroad practically throughout its entire length and when it was necessary to change the location these towers could be taken down and loaded on the cars. The wires and insulators would have to be removed in any case and, as the construction crew will be on the spot, it would take very little extra labor to remove the towers also. The length of span will be from

350 to 400 ft. (106.6 to 121.9 m.) and the height of tower from ground 30 ft. (9.14 m.). The size or character of the wire will not be settled definitely until the nature of our requirements is known. The current will be 22,000-volt three-phase, 60-cycle. At each logging engine there will be a portable sub-station containing one 150-kw., three-phase, 22,000-550-volt, step-down transformer. From the secondary of the transformer a three-core steel-armored flexible cable will be led to the motor. This cable will be built up in sections with suitable connectors until a limit of 1,800 ft. (548.6 m.) is reached, when it will be necessary to extend the line. This distance will permit of clearing a large area, as the steel logging cable has an effective reach of 3,000 ft. (914.4 m.). The motor will be of 150 h.p. capacity, and of the phase-wound type driving by means of friction pulleys.

A controlling panel with current-limiting relay to automatically introduce resistance into the rotor circuit in the event of the log striking an obstruction, will be installed on the platform beside the motor. This principle has been applied with success on electric shovel work and prevents the annoyance of a constantly tripping circuit breaker. A circuit breaker will be used to prevent damage to the motor should the power demand rise to an excessive value in the event of the obstruction proving beyond the capacity of the machine.

If successful there is scarcely a limit to the uses of a power supply carried into the forests and the natural outcome would seem to point to an extension embracing a complete electrification of logging railroads. Within four miles of Elk River there are two waterfalls of 85 and 102 ft. (25.9 and 31 m.) respectively which could supply upwards of 5,000 h.p. There are numerous little settlements at present remote from any center of power supply, which doubtless would welcome the opportunity to secure energy to assist in development.

In submitting this paper to the A.I.E.E. the writer would appreciate any record of experiences of members in similar circumstances and would be glad to furnish any further particulars in his power on matters relating to the electrical side of the lumber industry.

DISCUSSION ON "ELECTRICITY IN THE LUMBER INDUSTRY." LOS ANGELES, CAL., APRIL 27, 1911.

R. L. Noggle: I might say just one word in favor of electrically operated sawmills, and that is this: You will find that in using electricity, in place of steam you will save on your insurance. Where I am in the northern part of Idaho, we have started to furnish power to two different mills which consume some 750 h.p. The only talking point we could impress them with at all was that of insurance. We are running our plant entirely on refuse and shavings from the saw mills and in turn sell those people 600 h.p.

J. A. Lighthipe: I think the advantage in the lumber industry, if electrically operated, is not so much in operating the sawmill as it is in supplying power to the logging camp. For years they have been trying to get hold of a large portable saw that would take care of the logs. I would like to ask how they have succeeded. They saw up a tree seven or eight or nine feet in diameter, and the question of operating those saws is quite a question. We made a failure at Folsom, not so much in operating the mill as in the lack of logs to saw. At that place we had a great dispute over the amount of power necessary to saw. The boss sawyer used to take a log and jam it through as fast as he could. He would crowd the mill to the utmost. That is about the last experience I have had with any large logging concern. Inquiries have come from the neighborhood of Seattle to know if anything had been developed for an electric saw out in the lumber camps, away out where they drop the logs and section them up. That is where it is needed more than anywhere else.

C. Pemschel: In the first part of this paper in which the author describes the installation at the Elk River & Potlatch Lumber Company, he informs us the hand mills vary in horsepower from 30 to 275 h.p.

I think it would be very interesting for us to know the horse power under the different conditions that the mill is operated. The size of the cut and feed. This same thing also applies to the edges. I also notice that he says that the planers in the planing mills are driven by 75-h.p. motors. Seventy-five horsepower is rather large for the largest size planers and I surmise that one 75-h.p. motor drives a group of planers. Any information that he has, that is, the horse power, that these planers take under actual operating conditions I am sure would be very interesting to the readers of this paper.

The second part of this paper in which electric logging is taken up is interesting to me as I have given this matter considerable consideration and thought and have worked out the scheme of operating these donkeys by means of compressed air and last July read a paper before the Logging Congress in Portland on this subject. A copy of this paper can be seen in the August issue of *The Timberman.*

J. A. Lighthipe: Seventy-five horse power is nearer right than twenty-five.

The tendency in all of the mills is to force the machines. Power is very cheap and time is very costly and they are apt to overcrowd everything. I found that particularly in the great big band saws where the boss sawyer was trying to drive the logs through as fast as he could. The planers did the same way. They fed those machines up to the limit. The work in these camps is not to be compared with any railroad shops you ever saw. The lumber is cheap, power is cheap, and labor is high.

Ralph Bennett: It appears to me that you were using your planer for resizing. Taking off some very heavy cuts to get a different sized material. That need not occur in a lumber yard or at the mill.

I installed about two years ago a rather large planing mill for this district in which we used electric drive throughout, and turbines for generating. That mill has 40 h.p. on each planer, and they handle the material very nicely.

In this same connection I investigated the possibility of using electric power in their saw mills, and installed a 300-kw. turbine in what they speak of as Mill B. They propose to rebuild Mill A, or build a new mill electrically driven. We found that the 250,000 B. M. mill took about 900 h-p. running idle, 1100 on normal load, and possibly 200 more when all three bands happen to catch at once. The amount of power given in this paper for the bands would not be at all applicable to Pacific redwood mills.

The Potlatch method of logging must also differ somewhat from that used in the redwoods, because it is necessary there to handle not only a logging engine but a yarding engine. The logging engine could be reached by a wooden pole line along the railroad. The yarding engine is, however, three thousand to five thousand feet beyond the road engine on a steep hillside, without any permanent surroundings whatever, and it would be necessary to reach it with a cable. These logs are at present sawed by hand where they are felled. Indeed an enormous possibility in labor saving in the woods exists here. Fuel for the road engines represents less investment than fuel to the yard engines. The road engine is reached by an oil tank car, but oil has to be packed to the yard engine. This oil is brought from Southern California, and taken into woods where they are burning their waste to get rid of it.

At the mill it is true that fuel is valueless. It is also true that the cost of preparing and firing wet sawdust is high. There are times when steam cannot be kept up. By feeding more of this material to refuse burners, and less to the boilers, it can be disposed of at much less cost. The economy of high grade turbines is therefore an advantage after all.

Most modern engine-driven mills have two engines, one for the front and one for the back of the mill. A breakdown in either engine shuts the mill down. Two turbines of the same capacity, both running, would be but part loaded. A breakdown on either turbine would permit the running of the remaining installation with the uninjured turbine.

The author of the paper speaks of the use of storage battery locomotives in the yard. There are now in operation in California and in the southern states, a great many monorail systems, in which the car travels on an I beam rail elevated 25 or 30 ft. above the yard. When properly installed, this will cover the entire storage area, permitting it all to be used for lumber storage purposes. If lumber is piled in stacks in proper shape and tied together, it can be handled into the pile and stored without any hand shoving whatever, and still in the package taken aboard the vessel or car and so transported as a unit from the sorting table to the wholesale lumber yard, thus reducing the cost of handling and storage to a minimum, at the same time producing under proper conditions a much better grade of lumber with quicker handling.

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A POWER DIAGRAM INDICATOR FOR HIGH-TENSION CIRCUITS

BY HARRIS J. RYAN

INTRODUCTION AND SUMMARY

The power diagram indicator was produced as a feasible, inexpensive instrument to observe dielectric or similar stray power losses that occur in high-tension circuits.[1] A cathode ray-pointer is used to trace the power diagram. It is actuated electrostatically. The pressure of the high-tension circuit applied to " quadrants " causes a proportional displacement of the ray-pointer in one axis; the pressure drop between the terminals of a condenser in series with the high-tension circuit is applied to the other pair of quadrants and gives the ray-pointer a quadrature velocity proportional to the current. The ray-pointer is thus made to trace a diagram that encloses an area proportional to the e.m.f.-current-time product.[2] Alternating current will produce a closed diagram or " card " having an area which is proportional to the energy of the circuit delivered per cycle. At constant frequency, therefore, the card-area measures the power applied in the circuit. The form of the card tells of many things besides the amount of power just as the steam engine indicator card does in steam engineering.

The pressure and current ranges of the instrument are controlled by values of the capacities of the condensers employed. The capacities of the operating condensers may be varied indefinitely so that the working range of the instrument may be varied also indefinitely. The instrument was used to measure the dielectric loss that occurred in a one-quart (0.946-liter) sample of insulating oil, caused by moisture or other impurities. The values encountered were 0.03 watt at 9,000 volts. See Fig. 9. This is the smallest high-tension power measured in the trying out tests. The highest power measured was a corona loss of 750 watts that occurred at 130,000 *root-mean-square approximate sine-wave volts* on a high-tension laboratory line. See Fig. 7.

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[1] The instrument may also be employed as a dielectric hysteresis diagram indicator as discussed under *Theory*.

[2] For those who prefer it a mathematical demonstration of this relation has been given under *Theory*.

The *integrity* of the instrument depends upon the quality of the condensers employed. If the condensers are good the indications of the instrument may be relied upon fully. The *accuracy* of the instrument depends upon two things:

1. The uniformity of the electrostatic fields set up by the deflecting quadrants.

2. The variation in the potential delivered by the electrostatic machine that is used to produce the ray-pointer. This causes a slight corresponding variation in the deflection of the ray-pointer.

In regard to both these causes of error it may be said that where but little care has been used in mounting and adjusting the quadrants and in operating the electrostatic machine the errors remain *within* 5 *per cent.* An accuracy that is sufficient for this class of work is, therefore, easily attained.

The indicator is conveniently calibrated by loading the test circuit for a known amount of power or by computing its scalar constant from its inherent constant obtained at low pressure and the capacities of the condensers employed.

The instrument has been found satisfactory for the study of high-tension insulation and insulators, dielectric losses in high-tension transformers, insulating qualities of transformer oils as affected by moisture, suspended impurities, etc., losses into the atmosphere from high tension lines, etc.

The principles of construction and operation, source and cost of this instrument are given under *Structural Details.* It is comparatively inexpensive, and an ordinarily capable person should have no difficulty in operating it to his entire satisfaction.

In closing, mention is made of the corresponding type of power diagram indicator operated magnetically using inductance in lieu of capacity control. Such an instrument is satisfactory only when operated on low-tension circuits. Because there are abundant facilities for work of all sorts on low-tension circuits, the magnetic form of this instrument is, at present, of comparatively little importance. The ray-pointer may also be operated by a combination of static and magnetic action from which additional forms of power indicator are made possible.

THEORY

In Fig. 1, u is a pointer that traces the diagram $x\ y\ x\ y\ x$. In so doing its motion is made up of two rectangular components determined by the following relation referred to o, the pointer's normal zero position:

The vertical displacement of the pointer, y, is proportional to the instantaneous value or the e.m.f., e, in a given alternating current circuit. By calibration these become equal.

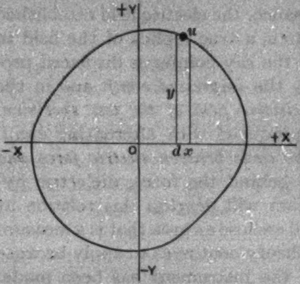


FIG. 1

The horizontal velocity of the pointer dx/dt is proportional to the corresponding instantaneous current, i. By calibration these also become equal. Thus

$$e = y$$

$$i = \frac{dx}{dt};\ dx = i\,dt$$

And $e\,i\,dt = dw =$ *energy increment*

Substituting $y\,dx = dA =$ *area increment*

Therefore $dA = dw$

Integrating $\int dA = \int dw$

Wherefore $A = W$, *i.e. area = energy.*

It follows that at constant frequency the areas in these cards by calibration equal the electric powers that produced them.

Cathode rays actuated electrostatically by means of four quadrants are employed for the ray-pointer. See Figs. 2 and 18. Between two opposing quadrants an electric field is established by the application of the e.m.f. impressed upon the testing circuit. Thus a displacement of the ray-pointer is produced, proportional to the applied e.m.f. The remaining quadrants are connected to the terminals of a condenser in series with the testing circuit. By this means the ray-pointer is placed in the presence of a quadrature electric field that is due to the pressure drop produced in the condenser by the testing circuit current. The rate of change of such pressure drop, and therefore of the electric field, is proportional to the current and the ray-pointer is thereby given a quadrature velocity that is proportional to the current. An instrument thus arranged and operated behaves in accordance with the above theory.

Theory for the Dielectric Hysteresis Diagram Indicator. When the specimen is a dielectric through which the test pressure sets up current only by condensance, the electric field established between the velocity quadrants is a true replica of the field in the dielectric. It is then that the ray-pointer is displaced proportionally in one direction by the *impressed e.m.f.* and in the quadrature direction by the *electric field of the test specimen.* The resulting diagram when produced with alternating e.m.f. gives *the relation throughout the cycle between electric force and electric field.* If the field lags behind the force, dielectric hysteresis is present. The diagram will develop this relation at every phase of the cycle. It will enclose an area that is a measure of the hysteresis. The above theory continues to apply because no change in the operation of the instrument has been made. The area of the card, is therefore, proportional to the energy lost through dielectric hysteresis per cycle and to the corresponding power lost at constant frequency. The application specified under *Methods*, Fig. 8, is an example of the way in which the instrument may be used to secure dielectric hysteresis cards. Manifestly if conductance is present the card will include the form and area due to a combination of both losses. A corresponding difficulty arises in the use of a magnetic hysteresis diagram tracer.

METHODS

The cathode ray-pointer is made up of electrons discharged from the cathode at a negative potential around 10,000 volts. The potential, however, of the speeding electrons is zero having been lost by acquiring a "velocity due to (electric) head" just as is the case with a water jet in hydraulics. It follows that for best results the middle values of the displacement and velocity pressures applied to the instrument quadrants and the cathode ray-pointer should all have a common "zero potential".

It is best, therefore, to cover the electrostatic machine, used to produce the cathode ray-pointer, with a wire net and to ground such net and the positive terminal of the machine; and to divide the velocity condenser into two parts, connected in series at the center of the source or at the center of the test circuit, with the connection between the condenser parts also grounded. This will balance the behavior of the ray-pointer in the presence of the four quadrants. Obviously a source which through accidental grounding, faulty insulation, etc., presents an e.m.f. that is unbalanced with respect to earth potential and is not so convenient. In such case it is necessary that the mid-potentials of the displacement and velocity pressures and the potential of the ray-pointer have a common value. The exact details to accomplish this depend upon the particular circumstances and must be left to the intelligence of the experimenter. Fig. 2 gives the connections when the velocity condensers are connected at the middle of the source and Fig. 3, when connected at the middle of the testing circuit.

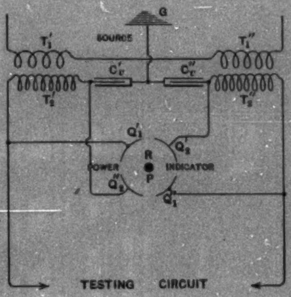


Fig. 2

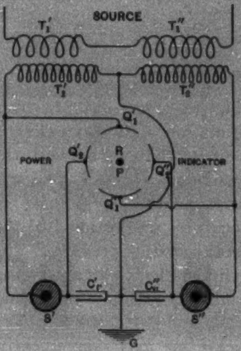


Fig. 3

The e.m.f. that will deflect the ray-pointer over the maximum range depends upon the dimensions adopted and the manner of mounting the quadrants. It can be made as low as 200 volts, maximum. It is 900 volts, maximum, in the instrument that was used for the trying-out work referred to herein. See Fig. 18. As the instrument is suited primarily for high-tension work it follows that a pressure range multiplier must generally be used. Some form of condenser-type multiplier is best for this purpose.

Fig. 2 is repeated in Fig. 4 and the pressure multiplying condenser, C_d^{I} C_d^{II} C_d^{III} C_d^{IV}, has been added. This is called the displacement condenser as used in the trying-out experiments. A photograph of this condenser is reproduced in Fig. 5. It is an air-dielectric condenser. The electrodes, C_d^{I} and C_d^{IV}, were made, each of four 7-ft. by 5-in. (2.133-m. by 12.7-cm.) cylinders of galvanized sheet iron, electrically connected. To form the spherical ends of the cylinders, float balls were used, such as are employed in household plumbing. Between these electrodes the source-pressure establishes an electric field. Midway between them is mounted a ground plate *o o*, and on either side two field tapping plates, C_d^{II} C_d^{III}, which are connected to the displacement quadrants, Q_2^{I} Q_2^{II}. In this way an exact replica miniature of the large electric field is produced between the quadrants, Q_2^{I} Q_2^{II}, that will displace the ray-pointer in accurate proportion to the total source of pressure. The cylinder-electrodes are swung from a frame by insulating cords and by means of pulley tackle one may conveniently adjust the positions of the cylinders from the floor so that they will be near to or far from the tapping plates, C_d^{II} C_d^{III}. Insulating cords suspend the tapping plates on either side of the ground plate, *o o*, in such a manner as to draw them together. Hard rubber set screws are used to determine their separation from the ground plate as shown in the photograph. In this way the maximum pressure range of the instrument is quickly adjusted from 900 to 250,000 volts.

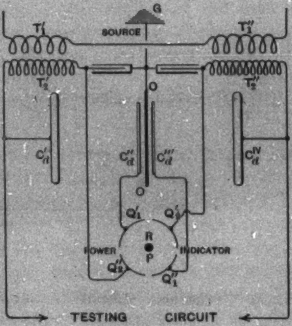


FIG. 4

When the velocity condensers are connected at the center of the source, see Fig. 4, and the testing circuit is open, the instrument will indicate *no power*, provided there is no dielectric loss in the transformer, displacement condenser and their connections. It will indicate the vector-sum of the combined charging current of the high-tension circuit of the transformer and the displacement condenser at the delivered e.m.f. It will indicate each of these, *i.e.*, by the velocity or displacement of the ray-pointer, according as one or the other is short-circuited out. The air-dielectric pressure condenser is easily insulated so that it will display no dielectric loss. Good transformer oil, free of water, which will break down at 50,000 volts between half-inch (12.7-mm.) spheres separated one-tenth inch (2.54 mm.) caused the 120,000-volt transformer outfit employed in this work to operate at full pressure without appreciable dielectric loss. When, however, there is present a dielectric loss in the source transformer it must be observed when the testing circuit is cut out at each particular voltage and a corresponding correction must be made.

FIG. 5

The method wherein the velocity condensers are connected to the center of the source is preferred, especially where it is not practicable to make the corresponding connection at the middle of the testing circuit. The measurement of the power lost in corona about a high-tension transmission line is an example of this sort. The nest of power cards given in Fig. 6 was obtained through an early trial of this method. The test specimen was the atmosphere surrounding a laboratory line with the following specifications: diameter of conductor 0.085 in. (2.159 mm.), interaxial distance 12.5 in. (31.75 cm.) length 130 ft. (39.624 m.). Card *I* has no area; it was taken at 44,000 root-mean-square approximate sine-wave volts, just before the atmosphere about the line broke and just below the pressure at which the card began to open out with an area. Card *II* was formed at 53,400 volts and card *III* at 64,000 volts. The cards in Fig. 7 were also obtained by this method. In this case card *III* was made at 128,000 root-mean-square approximate sine-wave volts, by the atmosphere loss about a laboratory line having the following specifications: conductor 5/16 in. (7.938 mm.) diameter, seven-strand, tinned, steel guy cable; interaxial distance 36 in. (91.44 cm.), length 128 ft. (39.014 m.). Cards *I* and *II* were formed by known loads applied in the testing circuit for calibrating purposes. Card *I* was made by the core loss of a 60,000-volt transformer applied on the high-tension side; Card *II*, the same plus load of seven 16-c.p., carbon filament "calibrated" incandescent lamps connected to the low-pressure secondary of the loading transformer and arranged so as to operate at about normal candlepower. The results herein obtained are given in the following table:

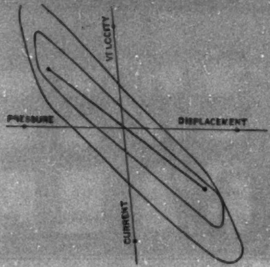
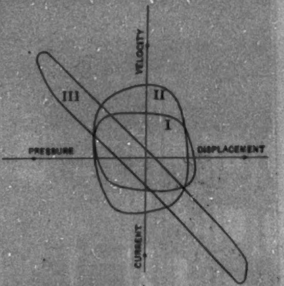


FIG. 6



I— 716 watts at 60 kilovolts, 0.350 sq. in.
II—1136 " " 60 " 0.546 "
III— 750 " " 130 " 0.360 "

FIG. 7

	Areas of original cards in sq. in.	In sq. cm.	Calibrating loads in watts	Watts per sq. in. by calibration	Watts per sq. cm. by calibration	Observed corona loss in watts
I	0.35	2.26	716	2050	317.88	—
II	0.546	3.52	1136	2080	322.22	—
III	0.36	2.32	—	—	—	750

The formation of an area in the power diagram began at 112,000 volts corresponding with the start of the "*noise*" and a few per cent under the pressure that started the visible corona.

Where the specimens under test take a small charging current and the dielectric losses are comparatively small it is best to arrange them in a testing circuit so that the velocity condensers can be used at the potential middle of such circuit rather than at the middle of the source-transformer. In this way the presence in the velocity condensers of the transformer and displacement condenser charging currents is avoided, making the indicator solely responsive to the dielectric properties of the specimens. The application of this method is perhaps best illustrated in the arrangement adopted for testing transformer insulating oils, shown diagramatically in Fig. 8. The specimen of oil is divided and placed in a duplicate pair of tinned pans. The pans are mounted over a metal ground plate, $O' O'$, and separated therefrom by an air-dielectric space sufficient to form the velocity condensers as shown in the illustration. Bits of new empire cloth, thin sheets of hard rubber, etc., do very well to support the oil pans and to form the condenser gap. The radius of curvature of the edges of all metal parts must be large enough so as to be far within the corona formation limit in either the air or the oil. To try out this method a

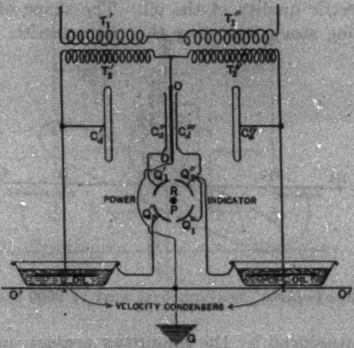


FIG. 8

specimen was selected from a supply of oil that had been exposed to the atmosphere in the laboratory and which had plenty of opportunity, therefore, to absorb moisture. On test at 9000 root-mean-square approximately sine-wave volts, by this method, card *I*, in Fig. 9, was obtained. The area of the card corresponds to about .03 watts. The oil was then taken from the pans, tested with lime to remove the water and after filtering was replaced in the pans and the test repeated. At 9000 volts the pressure that gave card *I* in the first test now gave the right line, *II*, showing no area and, therefore, no loss in the oil. The pressure was raised to 13,000 volts and the right line, no-area card increased from the limits, *II II*, to *III III*, showing that the dehydrating and filtering had made a vast improvement in the dielectric quality of the oil. The shape of card *I* tells an interesting story regarding the characteristic conductivity of the oil introduced by the impurities present, mainly water.

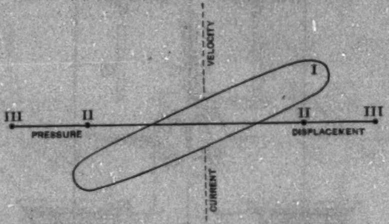


FIG. 9.—*I*—Area, measures 0.03 watt at 9000 volts

Those who are particularly interested in these matters will be amply paid for their time and effort spent in making their own comparative studies of the cards in this and the two preceding illustrations.

One other experiment was made to try out this method wherein the velocity condensers are connected at the middle of the testing circuit. The purpose of the experiment, in addition to trying out the method, was to determine whether soot on a wire would constitute the "dirt" and that is said to lower the e.m.f. at which corona loss begins.

Two steel wires, W' W'', Fig. 10, were mounted each at the axis of a 10-ft. (3.048 m.) length of ordinary 6-in. (15-24-cm.) stove pipe placed over a common ground plate. The relative positions of the pipe and ground plate were quickly adjusted so that the velocity condensers thus formed had the requisite capacities to produce a desirable current-velocity ray-pointer deflecting range. The source pressure was put up until the double line on the indicator screen parted to form an area thus indicating the fact that a zone of atmosphere about the piano wires had broken down causing a loss in power. After noting the source pressure that did this to be 22,000 root-mean-square, approximate sine-wave volts, it was turned off. A lighted candle was then attached to a suitable carrier made of soft copper wire, hooked to the piano wire and adjusted so that the flame would smoke it. By means of a string attached to the carrier the candle was made to pass under and smoke the whole length of each wire. Pressure was again applied to the wires and increased to the point where the indicator showed the start of a loss card,—this pressure was observed to be 24,000 volts. The increase was evidently due to the appreciable increase in the diameter of the conductor produced by the covering of finely divided conducting carbon. It was the first experiment in which this method was tried out and determined that soot is not the kind of " dirt " on a conductor that will lower the value of the e.m.f. at which corona is first formed.

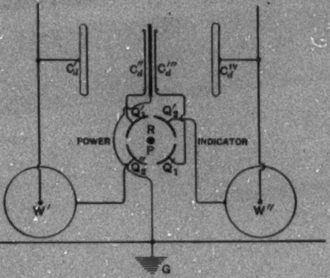


FIG. 10

At times it may be necessary in order to use the indicator to connect it on one side of the circuit in the same corresponding manner that a wattmeter is ordinarily connected. This can be done provided:

1. The indicator will produce true cards when the displacement and velocity quadrant potentials are entirely above or below the zero potential of the ray-pointer.

2. The conditions are so adjusted that the "ground" of the indicator with its electrostatic machine and the connections of the displacement and velocity condensers on the low-potential side of the line are at the same potential.

The first proviso was tried out at low pressure with the connections shown in Fig. 11. The source pressure, e, was applied to the quadrants, $Q' Q''$; the terminals of the velocity condenser C_v were connected to the remaining quadrants, $Q_2' Q_1''$; R was the loading resistance and I the instrument for reading the current. The power applied in this testing circuit was, therefore, I^2R.

Two cards were obtained, one at a given value of current I, and another at double that value or four times the power, *i.e.* $4I^2R$. These cards are reproduced in Fig. 12. The areas of the originals measured 0.067 sq. in. (43.21 sq. mm.) and 0.282 sq. in. (181.93 sq. mm.), respectively. The ratios of these areas is 4.21 to check with 4 which is a better behavior than was anticipated, especially because one of the areas traced was so small. There has been no opportunity as yet to try out the second proviso; however, with that no particular difficulty is anticipated. At all events in this repect the method will easily be applicable for detecting dielectric losses in all cases where one side of the source can be grounded.

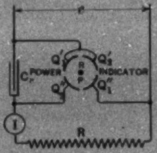


FIG. 11

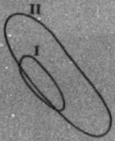


FIG. 12

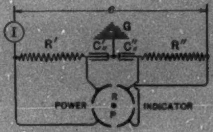


FIG. 13

The cards in Fig. 12 were obtained with neighbor-mounted quadrants; the ray-pointer that traced them was actuated by a composite field. For this unbalanced or onesided method of using the power indicator it is expected that better results will be obtained by tandem-mounted quadrants. With these the ray-pointer will be acted on first by one field and then by the other. Thus and by screening out the stray field set up by the high tension line, one should secure excellent results.

Originally it was not thought that the one-sided method would work. For this reason it was tried out only at the close of the series of trials merely for the purpose of working to the limits of the investigation assigned at the outset. When it was found to be quite feasible time did not permit to try out the method on high-tension circuits. A good testing load for such a trial would be a single high-tension line insulator. With the neighbor-mounted quadrants the cards must occupy one corner of the indicator screen; at all ranges they are, therefore, rather too small for comfort. The use of tandem-mounted quadrants should restore the use of the whole screen and the method should then approach the satisfactory character of the central connection method.

Accuracy and Integrity Trials

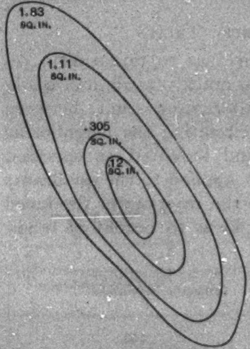
1. The character of the electric field as to uniformity, set up between a plain pair of quadrants, quickly made and easily mounted, was tested by applying alternating e.m.f. between one pair of quadrants and short-circuiting the neighboring pair. The quadrants were made and mounted as specified under *structural details*. The e.m.f's applied to the quadrants and the corresponding deflections of the ray-pointer produced were read and scaled and tabulated so as to permit of ready comparison. See table *I*:

Volts	Indicator deflections
140	150
280	271
420	413
560	556
676	688

This was not a complete accuracy trial. Composite fields deflecting the ray-pointer by the combined action of all four quadrants should also have been used. This test, however demonstrated that the accuracy required in the instrument is comparatively easy to obtain by a proper mounting of the quadrants. There is almost no end to the variation of the actual forms that may be given the deflecting quadrants. It is merely a question of putting enough time into the undertaking to produce quadrants so formed and mounted that the ray-pointer will be deflected with any reasonable degree of accuracy that may be desired.

2. The relation between areas and loading watts was tried

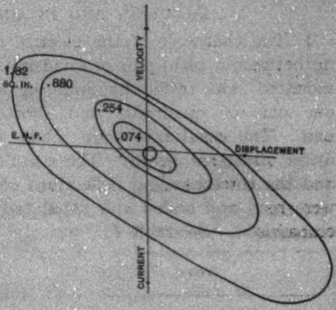
out with low pressures. The connections used are shown diagramatically in Fig. 13. The loading resistances R_1 R_2 were the ordinary "multipliers" used with alternating current instruments of the dynamometer type. The current through the loading resistances was read by means of the instrument, *I*, for which an ordinary alternating-current voltmeter was employed. In this way the nest of cards in Fig. 14 was obtained by making the proper changes in the loading current as indicated at *I*. The area of the original is given for each card. Fig. 14 also includes an "Integrity Table", *i.e.* a table of the card areas and the squares of their corresponding currents which are proportional to the power present and scaled so as to facilitate comparison. No attempt was made to secure higher proportional conformity of areas and the powers that produce them. The sort of work for which the instrument was developed does not require it. However, should it be so desired greater accuracy can be obtained by refining the method of making and mounting the quadrants and by screening the ray-pointer from the action of all stray electric fields.



Integrity table

	Powers.	Areas.
$38^2 \div 11,500 =$	0.125	0.120
$60^2 \div 11,500 =$	0.315	0.305
$110^2 \div 11,500 =$	1.070	1,110
$145^2 \div 11,500 =$	1.830	1.830

FIG. 14



Integrity table

	Powers.	Areas.
$31.5^2 \div 11,500 =$	0.086	0.074
$59^2 \div 11,500 =$	0.302	0.254
$100^2 \div 11,500 =$	0.870	0.880
$147^2 \div 11,500 =$	1.880	1.820

FIG. 15

3. With the arrangement of Fig. 13 but with potentials

unbalanced the nest cards given in Fig. 15 was obtained. The area of each card is given and an integrity table for the comparison of areas and corresponding powers is given as before. No important interference with the accuracy of the instrument was produced by such unbalancing effect. It is only necessary to secure an approximate balance, such as can easily be recognized by the eye when noting the form and location of the card on the indicator screen.

OTHER TRIALS

1. In Fig. 16 is given a nest of cards formed by the core loss of a 60-kilovolt, 20-kw., transformer supplied from the high-tension side.

2. The indicator accords means for the detection and approximate measurement of extraordinarily small amounts of power. The card in Fig, 17 was produced by an e.m.f. of 83 volts applied through *three megohms* or .0023 *watts*. The e.m.f. applied in the velocity condensers was 172 volts and the total source e.m.f. was 191 volts. In high-tension work where the multiplying displacement condensers would be used this corresponds to 2.3 watts at 191,000 volts. The loading resistances in this case were a pair of lead pencil " marks " about 5/16 in (7.938 mm.) wide and 8 in. (20.32 cm.) long made on linen writing paper. Their combined resistance when impressed with 108 continuous volts was determined by direct current voltmeter and portable galvanometer to be 3,000,000 ohms. Each of the pair of velocity condensers was made by laying an 8½-in. by 11-in. (21.59-cm. by 27.84-cm.) sheet of common typewriter linen paper as the dielectric upon a ground plate for one electrode and the other electrode was made by placing on top of the sheet a piece of tin foil 7-in. by 9-in. (17.78 cm. by

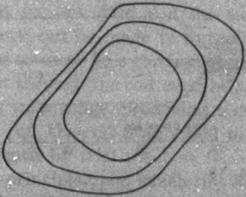
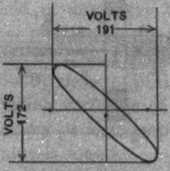


FIG. 16



AREA MEASURES .0023 WATTS

FIG. 17

22.86 cm). The limit of sensitiveness is attained only when the current-velocity quadrants of the indicator are made to serve as the velocity condensers. When that is done the sensitiveness of the instrument is such as to permit the detection of extremely minute powers, viz.:

3. As already stated for these trials, on purpose, no special care was taken in forming, mounting and insulating the quadrants. They were held in place on the glass of the tube by means of rubber bands.

Naturally according to weather conditions, the outer glass surface would collect some moisture and become conductive. When in this condition it is always interesting to apply alternating pressure to one pair of quadrants, with the remaining pair disconnected and to watch the drying off process that followed. It would be completed in perhaps a second. At the start off there would be formed a considerable card area due to displaced electric fields set up by leakage current from the charged quadrants that had an in-phase power component because of the resistance of the leakage path. The generated heat would evaporate the moisture at a rapid rate and the card areas would diminish correspondingly until after a second or so nothing remained but the right-line band due to the applied pressure. The amount of power indicated in these cases was extremely small.

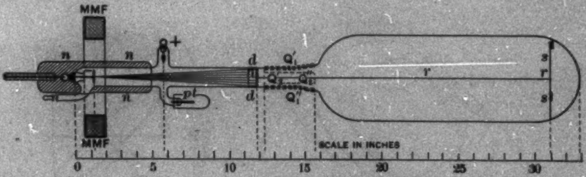


Fig. 18

It follows, therefore, that by proper refinement the indicator may be relied upon to detect the extremely small stray losses that are often responsible for serious damage to insulation.

Structural Details.

A drawing to scale of the cathode ray tube used as an electrostatic power indicator in these trials is given in Fig. 18. In view of the fact that there is no general familiarity with the source and character of the apparatus it may be well to add that this tube is made and marketed by Richard Müller-Uri of Braunschweig, Germany, catalogued by him as "Braun-Ryan No. 2761" and sold in Germany for twenty dollars.

A cone of cathode rays, *c r*, is emitted from the disk-shaped negative electrode. At the aperature, *a*, in the aluminum diaphram, *d*, a conical pencil of these rays, *r*, is allowed to pass, striking the screen, *s*, causing a fluorescent spot of light. These rays can be concentrated at the aperature, *a*, and focussed on the screen, *s*, to a marked degree by means of the magnetic field set up by the continuous current circulating in the coil m.m.f. The coil should have proportions somewhat as shown in Fig. 18. It should have a continuous, maximum m.m.f. capacity of about 2500 ampere-turns. To begin with, the central plane of the coil should be at right angles to the axis of the tube and near the negative electrode disk. The coil should be given a mounting capable of universal adjustment so that its own field and the earth's field or any stray field combined can be made to have the proper relation to the ray-pointer so as to give the best focussing effect. The continuous current through the coil must be adjustable by rheostat initially over a wide range, producing a corresponding variation of the m.m.f. of the coil from 1,000 to 2,000, more or less, ampere-turns until by trial the best focussing value is found.

The principle upon which this focussing effect of the magnetic field depends is interesting. The flying electrons that constitute the cone of rays that emanate from the cathode, being electricity in motion, constitute electric currents and are acted on as such by the magnetic field. If the rays were parallel and not divergent they would pass through a magnetic field, in a direction parallel to the tubes of force undisturbed. Being divergent, they have a component motion at right angles to the magnetic field and behave just as electric currents at right angles to such field. The consequence is that every electron having a divergent path through the magnetic field is continually deflected by the field at right angles to the divergent component of its motion. The effect of the magnetic field is thus to whirl the electrons in circles, which when combined with linear motion imparted by the charged cathode, produces as a net result, spiral motions. By properly adjusting the position of the magnetizing coil and the amount of its m.m.f., it is practicable to make each electron describe a spiral which, in projection, appears somewhat as that drawn in Fig. 19.

By this means many more electrons are made to pass through the aperature, *a*, and to strike the same luminescent spot on the screen, *s s*, than would otherwise be the case. The spot or trace made by the ray-pointer is, therefore, much brighter than it would be without the use of the focussing coil. For the rays near the center of the ray-cone there is little or no divergence; away from the center there is more divergence. From the nature of things, this method of focussing can be made true but for one degree of divergence; it follows, therefore, that while it is effective in increasing the brilliancy of the ray-pointer and in lowering the potential at which the electrostatic machine must operate to produce the discharge, it cannot be effective to prevent materially the increase of the diameter of the luminescent spot which is always from two to three times the diameter of the aperature. Nevertheless it is a great help and should always be used[3]. The nest of power cards in Fig. 13 is reproduced at about two-thirds of the size of the originals as they appeared on the screen of the instrument. The little circle at the center is a trace of the outer circumference of a well focussed luminescent spot that produced the cards and which were recorded by tracing on smoked glass *to the center* of the band-diagram formed by the rapidly moving luminescent spot.

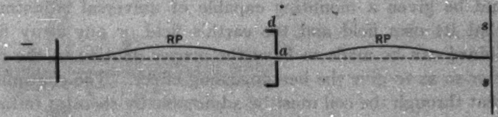


Fig. 19

The most important structural feature is the manner of connecting the negative electrode to the electrostatic machine. Ordinary good quality automobile high-tension ignition cable does very well for this purpose. Near the tube the ignition cables should be terminated by brass hooks in the manner shown in Fig. 20; and the connection should be remade

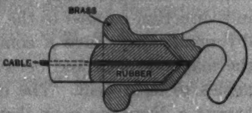


Fig. 20

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[3] Physicists have long known the general behavior of a cathode ray in a magnetic field. The author is indebted to Mr. Robert Rankin for the practical development of this system of focussing the cathode ray-pointer. Through much originality and enterprise, it was worked up by him as a graduate student in 1905.

pair of by linking the hooks. Electrostatic machines of the influence type, have a way of starting off in an uncertain direction. The hooks provide a simple, satisfactory means for reversing the connection. A photograph of the indicator showing the ignition cables joined by means of these hooks is reproduced in Fig. 21. It is important that all external edges of these hooks should be formed with an ample radius of curvature so as to prevent atmospheric conduction or corona loss discharge from the electrostatic machine. Such loss when it does occur is fitful, and gives rise to an irregularly sustained ray-pointer.

FIG. 21

The cathode terminal has a great tendency to produce atmospheric conduction right at the point where it enters the glass due of course to the high capacity of the glass which concentrates the field through the air films in that region to their breaking point, producing corona and in consequence an irregularly delivered ray-pointer. To prevent this an ample insulating jacket must cover properly the cathode end of the tube and the connecting cable as shown by cross section at *n n n n* in Fig. 18, and again by photograph in Fig. 19. The result of much experience with these jackets has been to determine that they are best made of paraffin, laid on hot by means of a brush, layer upon layer. It takes about two hours to build up the jacket in this way and when done, it is satisfactory and will last for months. After the operation is well under way the process can be hastened by sticking on pieces of glass tubing or good quality sealing wax and by pouring the well dried-out paraffin at a temperature that is just high enough to secure ample fluidity, into a paper mould formed about the part of the jacket already in place. Experience in casting the jacket complete in one operation has not been satisfactory.

When one of the tubes is used steadily a few hours daily for several months the "hardening" effect arrives that is known to all familiar with the X-ray tube. This is due to the increase in the vacuum produced by much use. When the vacuum is too high, the tube does not work so well, chiefly because of external corona loss,—besides it is liable to puncture. To lower the vacuum a small platinum tube, *p t*, Fig. 18, is sealed into the cathode ray tube at one end; the other end projecting outward is closed. By osmosis a little hydrogen may be passed through the platinum tube to the interior of the cathode ray tube when heated to red heat in an alcohol flame. The alcohol vapor conveniently furnishes the hydrogen. Care must be used not to admit too much hydrogen and thus lower the vacuum too much. The best gauge of the degree of vacuum is the electric pressure required to set up the cathode ray-pointer. The discharger balls on the electrostatic machine are conveniently employed for this purpose. A spark at ⅜ in. (9.525 mm.) gap or a little less between the discharger balls is a measure of a degree of vacuum that always gives excellent results. The balls are fixed firmly at ⅜ in. (9.525 mm) separation, so that in attempting to operate a hardened tube the machine will discharge at the balls and not through the tube. The alcohol flame is then applied to the platinum tube until it is red hot and immediately removed to await the effect. A little time should be allowed for the newly admitted hydrogen to disseminate throughout the tube. In a minute or so, if the sparks have not ceased between the discharger balls, a little more hydrogen should be admitted by reapplying the alcohol flame to the platinum tube, stopping the process each time, early, to note the result,—and so proceeding until the vacuum is lowered to the desired point, the ray pointer has been reëstablished and the sparks between the discharger balls have ceased.

A record may be made of the diagrams indicated on the screen of the instrument by photography or by hand tracing, either from the front or back of the screen. From the front the view is necessarily at an angle. Distortion is avoided by fixing the plane of the recording plate or sheet parallel to the plane of the instrument screen. The most convenient method that experience thus far has developed is to use a lightly smoked glass mounted on a small table or hand rest next to the body of the tube which must be mounted as shown in Figs. 21 and 22. A peep-sight as there shown fixes the point of view. The little table is made in the form of a shallow oblong box with ends opened and lined with white paper. At the middle an opening is cut and arranged so that the smoked glass can be mounted on the under part. Thus light can be admitted from incandescent lamps at the ends so as to shine on the point of a marking

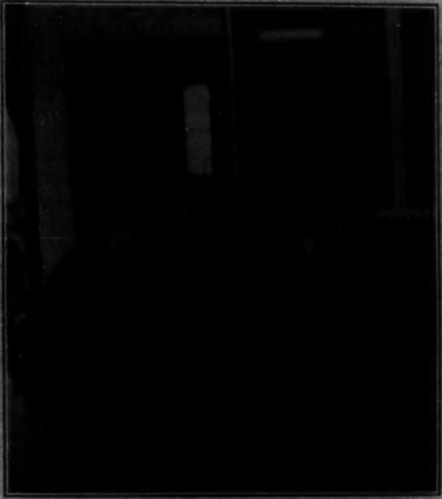

FIG. 22

stick to assist the eye in making the record. Many methods are available for making these records including the use of the pantagraph, planimeter, etc.

As to the electrostatic machine: Any good make of Wimshurst type electrostatic machine, having four or more pairs of plates, 15 in. (38.1 cm) in diameter or larger, of hard rubber, glass or mica, will do very well.

For work in the daylight it will be necessary to exclude the light very largely from the instrument and recording table. This may be conveniently done by means of a cloth hood held in place at the top by a drawing-in tape, parted and closed with hooks and eyes, furnished with openings to admit the ends of the recording table and a sleeve to admit the recording arm of the observer, as shown in Fig. 22.

As already referred to: it is best to cover the electrostatic machine with a grounded metal net so that stray fields from the high-tension circuit will not interfere with its work. It is best to look carefully to the setting of the instrument or to protect it by grounding metal nets, so as to relieve it from interference from the same cause. Again it is well to keep the ignition cables that connect the instrument to the electrostatic machine free from vibrations because the stray field they carry will correspondingly sway the position of the ray-pointer; or better, their stray field may be shut out also by means of a properly mounted metal grounded net.

THE CATHODE-RAY POWER DIAGRAM INDICATOR OPERATED AS AN OSCILLOGRAPH

It is often desirable to know the wave forms of the e. m. f. or current employed in the high-tension insulation tests or other work for which the electrostatic power indicator may be employed. This is easily accomplished for the e.m.f. wave by short-circuiting out the indication of the current-velocity field. The ray-pointer then has simply a displacement motion that is proportional to the e.m.f. from instant to instant. The wave form drawn in the familiar rectangular components may be viewed through a synchronously revolving mirror such as is employed in connection with the common Dudell type of oscillograph. Or it may be made to trace its time card by applying a sine-wave pressure tapped from a sine-wave current source[4] to the current-velocity quadrants. As the third harmonic is almost invariably absent from the ordinary three-phase source, pressure tapped from one of the phases of such a source will be approximately sine-wave, and may be applied to the velocity quadrants in lieu of the true sine-wave pressure to develop the oscillogram of the e.m.f. where great refinement is not necessary.

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[4] The Cathode Ray Alternating Current Wave Indicator, by Harris J. Ryan. TRANSACTIONS A.I.E.E., Vol. XXII, p. 539, 1903.

To produce an oscillogram of the current, non-inductive resistances, having values equal to the reactances of the velocity-condensers should be substituted in lieu thereof. Deflections of the ray-pointer will then be produced that are proportional to the instantaneous values of the current. The current wave form may then be observed and recorded by means of the revolving mirror, or the current may be made to produce its oscillogram by substituting, in convenient phase, a sine-wave pressure for the line pressure that was cut off from the corresponding quadrants when the start was made to oscillograph the current. Unless the pressure necessary to actuate the ray-pointer is small compared with the total impressed pressure this method will introduce errors that are small to begin with and which increase in an obvious mannner as the difference between the two pressures grow less. This may be avoided altogether by taking an oscillogram of the current-velocity movement of the ray-pointer which will not be so easy to interpret but which will have introduced no error.

THE MAGNETICALLY OPERATED POWER DIAGRAM INDICATOR.

A number of years ago Dr. D. K. Morris at the University of Birmingham, England, by the combined action of two Dudell oscillographs, produced hysteresis cards from closed laminated magnetic circuits actuated by alternating currents. To do this the magnetizing current was passed through one oscillograph and through the other a current was passed that was generated by a secondary coil mounted over the closed magnetic circuit and controlled by an inductance, as pure as it is practical to make. The ray-pointer of light was reflected from the mirror of one instrument and then from that of the other by a suitable arrangement of optical facilities so as to trace on the observing screen or recording plate a card of the hysteresis present in the closed magnetic core.

It is easy to perform this same experiment by means of the magnetically operated cathode ray oscillograph. One instrument does the work because the cathode ray pointer will at once follow both rectangular displacements, one proportional to the magnetizing current and the other proportional to the core-flux present. This was done in the Cornell laboratories for purposes of instruction in 1905. It was not recognized, however, at the time that such an instrument is inherently a power diagram indicator and that it behaves as such *when connected as in Fig.* 23.

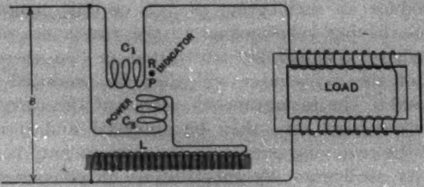

FIG. 23

The theory of this indicator is precisely the same as that for the electrostatic type except that magnetic fields are used in lieu of electric fields, and current and e. m. f. have exchanged duty in producing the displacement and velocity movements of the ray-pointer, *i. e.* in the magnetic power indicator the ray pointer is given a displacement that is in proportion to the line current and a quadrature velocity that is proportional to the impressed e. m. f. for a current that is controlled entirely by

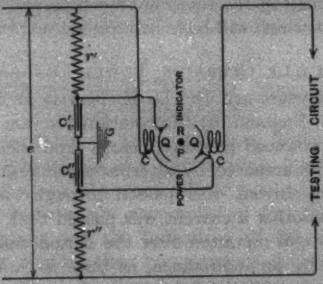

FIG. 24

inductance varies at a rate that is proportional to the impressed e. m. f., or

$$e = \frac{d\,i}{d\,t}$$

Finally it is apparent that a combination static-magnetic power diagram indicator should be possible and practicable. One such form that has suggested itself is shown diagramatically in Fig. 24 wherein the reactance of the pressure velocity condensers C_v' C_v'' must be small compared with the value of the non-inductive, noncondensive controlling resistances, r' r''.

This investigation was undertaken to provide a satisfactory electrostatic power diagram indicator to be employed to detect and measure stray power losses that occur in and often injure dielectrics employed in high-tension practice. There was no thought to produce a corresponding magnetic form of instrument. It came along with the undertaking as a sort of by-product and as yet no important need of it has been discovered. Doubtless in time it may prove to be of particular value in certain classes of work.

The author is happy to employ this opportunity to acknowledge his indebtedness to his co-workers, Professors S. B. Charters, Jr., and W. A. Hillebrand, for their hearty coöperation in making the trying out experiments herein reported and to the authorities of Leland Stanford Jr. University who approved the purchase of the equipment required for work of this character.

DISCUSSION ON "A POWER DIAGRAM INDICATOR FOR HIGH TENSION CIRCUITS," LOS ANGELES, CAL., APRIL 27, 1911.

E. F. Scattergood: I understand that this instrument is quite easily moved and therefore available for investigations in the field and I would like to hear something further in regard to the portability of the instrument. I feel that the profession is greatly indebted to Professor Ryan for the instrument which he has developed and presents as well as for the practical results he has secured from its use and presented by him last January.

C. L. Cory: I think you will agree with me that as Professor Ryan outlined to us the details of this instrument we enthusiastically admired the manner in which the result has been accomplished. Professor Ryan stated that in general the measurement of one watt at 100,000 volts is of little consequence in the practical operation of transmission systems. However, we are interested quite as much in being able to measure the indefinitely small quantities here indicated as we are in the accuracy of the measurement of the quantities ordinarily of interest in such systems. In his experimental work he has measured power at 9,000 volts amounting to only 0.03 of a watt. This would correspond at unity power factor with a current of 1/300,000 of an ampere. We are with this instrument capable of measuring the three hundred millionth part of the output of a modern 3,000 kilowatt steam turbine alternator, and it is quite as important sometimes to be able to measure these very small quantities as it is to accurately measure the larger quantities.

The instrument allows a beautiful analogy to the steam engine indicator. We have a horizontal line on the bottom which corresponds to the line of atmospheric pressure. We have a vertical line which corresponds to the variation of pressure. In Fig. 7, where the pressure approaches 40,000 volts, the diagonal line shows no energy. Beyond this the two areas, one larger than the other, indicates at which point the " thing turns around the corner ", so to speak. The instrument is one which it seems to me will have wonderful practical application. We have had indicated to us directly how insulators may be tested and I dare say we might quite as well use it to determine the dielectric constant of condensers. It is applicable to ordinary voltages quite as much as it is to our highest practical voltages. After all, that which is probably the greatest attainment, however, is the beautiful and accurate method whereby it is possible to measure accurately on the very highest voltage systems the smallest possible quantities and in addition to ascertain what is happening on the line as a result of the action of such small quantities of energy.

J. J. Frank: I see practical value in the use of this instrument in measuring losses at high potentials. At present we have no satisfactory means of measuring such high potentials because our instruments do not follow the variations in the wave-shapes of potentials. The only instrument we have is the spark-gap.

If this instrument of Professor Ryan's does recognize the wave-shape, it will certainly be of value in measuring losses on lines, in cables, dielectrics, oil and insulators, which is one of the important studies we now have before us in connection with high voltage transformers.

Ralph D. Mershon: Professor Ryan spoke in a very off-hand way of getting a known high voltage load with which to calibrate his instrument. I have often endeavored to get such a load that would be above suspicion, but have never succeeded. If Professor Ryan has devised some means of getting a high voltage load that will remain constant, and can be accurately measured, I shall be glad if he will tell us of it.

I should like to ask Professor Ryan whether he has investigated, by means of this instrument, the effect of moisture on the corona.

I desire to take this opportunity of expressing my appreciation of this paper, and my admiration for the work it evidences. With Professor Cory, I think the sensitiveness and accuracy are most astonishing, and should lead to extremely valuable results. An instrument of this sort should be well adapted to the study of insulation and what happens when it is subjected to electrostatic stresses. At the present time our knowledge in regard to dielectrics is comparatively limited. I believe one of the greatest problems before the Electrical Engineer today is the problem of insulation; that there is a possibility for great improvement over what we have now. What we would like to have, is an insulating material that can be worked like metal, and that will stand the temperatures most metals will, so that we can run our apparatus at something like the temperature of a steam engine. It seems to me, the further we get away from organic substances the more nearly will we approach a satisfactory solution of the insulation problem.

H. J. Ryan: I will take these questions up in the order in which they were given. As to the portability of this apparatus: In its present stage of development it is not very portable. An American instrument maker is now investigating it with a view to placing it on the market in a portable form should that be found practicable. In 1901 I transported an outfit of substantially this same sort from Cornell to Columbia to operate it magnetically as an oscillograph at the conversazione given by the American Institute of Electrical Engineers. In 1905 I again transported a similar, though a much more complete outfit from Ithaca to Pittsburg to deliver an illustrated lecture at the Electric Club on the uses of the cathode ray oscillograph. Those two experiences demonstrated that the outfit referred to in this paper can be considered as portable equipment, though it is certainly a long way from constituting a portable instrument in its present form.

I began ten years ago to look for a feasible electrostatic power diagram indicator. My great regret now is that largely through a feeling that such a thing was perhaps impossible, I failed to realize that I had at hand all the while the necessary expedients. These were employed just as soon as the principles were worked out upon which the power diagram indicator must operate.

Referring to Mr. Frank's question as to whether this instrument will recognize wave forms—it will do that very nicely. Alternating voltage applied between one pair of quadrants only will cause the ray-pointer to oscillate and the true voltage wave form may be observed by looking at the band of light thus produced on the screen. To do this transmit the image of the moving spot to the eye through the usual synchronous vibrating mirror. If preferred the ray-pointer may be given a sine-wave motion in quadrature with the motion imparted to it by the voltage. Thus an open card is formed of a known and an unknown motion. In that way the unknown voltage wave form that imparted the corresponding motion to the ray pointer becomes known. We can all realize this by remembering the steam engine indicator card. There the horizontal motion being reduced from the piston motion is known. The vertical motion produced by the steam pressure is unknown until the indicator card is produced by combining both motions when it is made known also. A sine wave current for this purpose is obtained by means of a " wave filter " described in my paper on the cathode ray oscillograph read at the 1903 Niagara Falls meeting. The ray-pointer is actuated magnetically by such current. If you are making accurate measurements of this kind, you would have to go into a careful arrangement of the electrodes mounted on the walls of the tube in order to make the spot deflect accurately in all regions; that is, to make the quadrature deflections in all regions proportional to the applied potential differences. That means not using a plate bent around the tube for the electrodes, but using parallel wires and distributing them around the tube until the electric field therein is entirely uniform within the range in which you are using it. For all ordinary work the quadrant will not have to be given such special construction.

As to objection to the internal losses in the high-tension circuit of the transformer when you apply the velocity to the condensers at the center of the same, instead of at the center of the samples: If the oil is clean, newly treated, has not been in the service, you will not find a loss such as you may expect. If, however, the transformer is not in this condition, *i.e.*, the oil has not been treated and put into proper condition for a test of this kind, then you obtain an area there that, under some circumstances, I am pretty clear could be cared for by subtracting; but it was on that account that I went after this method of using the sample itself only that is by working at the center of the sample. (See Fig. 8.)

Replying to Mr. Mershon's question as to what extent we may use this instrument for measuring high-tension line losses due to inphase current through the atmosphere—*i.e.*, corona formation.

We made some use of the instrument for corona loss measurements and have found that it does very well for such purpose. Measurements of sub-corona atmosphere line losses are difficult always because of the low power factor present. The instrument as it stands in this paper is at a corresponding disadvantage. When the power factors are small, one to two per cent, for example the corresponding power card is inconveniently elongated. To obviate this difficulty we have tried out an arrangement of velocity condenser that makes use of some of the line voltage for compensating the elongating effect of the reactive power. We found that this can be done and that wider cards can thus be obtained to indicate losses that occur at very low power factors and which otherwise would produce long narrow inconvenient and correspondingly inaccurate cards.

As to the axes not being at right angles in Fig. 6, that is due to the fact that our original try-out tests were just to see whether the thing would work. This was all done last spring. If we had had any notion in advance that the method would have worked out in this way, we would have taken a little more care. The quadrants were held to the outer walls of the tubes by rubber bands; they did not produce electrostatic fields that are exactly at right angles to one another because no effort was made to adjust them with exactness. These try-out integrity tests were made with this careless mounting of the electrodes, for the reason that I thought the apparatus would go into use, if at all, as something that we could bring together with comparative ease. As a matter of fact, it turned out much better in this respect than was anticipated. I did not have the time to make special tests for this paper, but took the tests which we had made in our former work. They are just as they were made in the original trials when we undertook to see how the method would work.

C. L. Cory: I would like to ask Professor Ryan if the fundamental work has not already been done to a sufficient degree so that we may very properly anticipate the use of this instrument, properly installed in commercial shape, in a substation for instance, so that experiments may be made on long distance transmission systems at different frequencies from 20 to 60 cycles and at different voltages from perhaps 30,000 up to 150,000 volts, not only on transmission lines which are practically level but on those crossing mountain ranges in which the different parts of the line are subject to atmospheric conditions which vary with the altitude.

What I am trying to bring out is the practicability of the instrument to determine questions not heretofore capable of satisfactory treatment.

Is it not true that the results to date indicate the possibility of the use of the instrument permanently installed in a substation for experiments on long lines in place of the one only 100 feet in length as used in your laboratory.

H. J. Ryan: I think that can be done. I believe, for my own part, it will be reduced to such convenient form.

R. W. Sorensen: Am I correct in my understanding that with an arrangement such as is shown in Fig. 23, the indicator can be used for measuring the core loss occurring in the transformer shown as load.

H. J. Ryan: The method given in that figure is for low-tension work entirely and it was put in here to round out this general scheme. If you can get a proper inductive control of the current in the circuit " L " then the area of the card should be proportional to the power that is applied to the circuit. The ray-pointer will then have a velocity proportional to pressure and not proportional to current; and it will have a displacement proportional to current.

R. W. Sorenson: In Fig. 8, for instance, the sketches marked " T ", etc., I presume are parts of a transformer.

H. J. Ryan: That is correct.

R. W. Sorensen: Would you measure on the transformer the loss due to the dielectric hysteresis, if the pans containing the oil sample were removed?

H. J. Ryan: If the sample were disconnected the ray-pointer would be given no velocity displacement, it would have a pressure displacement. A band of light would be formed on the screen due to such displacement being proportional to the terminal voltage of the transformer.

R. W. Sorensen: Then in Fig. 4—what would we get there, that we would not get with connections like Fig. 8, with the sample pans of oil left out.

H. J. Ryan: In Fig. 4 with no test specimen or other load connected the ray-pointer would be given a velocity movement proportional to the internal capacity charging current of the transformer and it would be given a displacement at right angles to such velocity proportional to the transformer terminal voltage. The result would be a card that would constitute a certain kind of measure of the high voltage dielectric loss in such transformer.

R. W. Sorensen: The reason I asked these questions was that about two years ago I tried to find out what was happening in a high voltage transformer. That is, it seemed to me, according to some work we had, that there is always a certain amount of energy transmitted through the dielectric. In some instances, it does not amount to much. In the case I have in mind the transformer happened to have four sections. When those four sections were in series, there was three to five per cent more core loss by test than when those windings were broken up in sections. I said the greater part of that must be dielectric hysteresis loss. What I am getting at is, can we measure with your instrument the dielectric hysteresis loss only and thus eliminate the error of subtracting one large quantity from another to get a small one as was done in the test to which I refer?

H. J. Ryan: If you lay the case of the transformer open, even in the California climate during the summer, it will show you, in a hurry, a nice fat card.

R. W. Sorensen: But it measures only the hysteresis loss; and not any other losses?

H. J. Ryan: Yes, it measures only the dielectric hysteresis loss. Certainly such is the case after subtracting the $I^2 R$ loss that occurs in the high tension winding due to the circulation of the internal capacity charging current. Unless the oil is in the very best possible condition such dielectric loss, we have found may be considerable.

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THE COST OF ARC LIGHTING AND GENERAL SERVICE FROM MEDIUM AND SMALL SIZE MUNICIPAL OR PRIVATE PLANTS

BY W. EDGAR REED

Much attention has been given to the large power plant in technical publications. This paper, on the other hand, will consider the costs of lighting and general service from the numerous small plants where the cost of service is so frequently and persistently referred to, not only before the plants are constructed but periodically during the operating life and also every time a lighting or power contract is let, a new unit is added or other extensions are proposed. As an example of this, at every renewal of arc lighting contracts with private plants there is generally severe competition and rates must be right to retain this business. Franchises for lighting and power generally go with the arc lighting contract, and if the latter business is lost, competition in all other branches is immediately introduced. This means furnishing arc lighting at little or no profit in many cases in order to retain the incandescent and power business which should in this case make a profit for the entire plant.

Since the active uniting of small plants was started, this question of costs has been presented more frequently than formerly and is of interest to both the large and the small plant.

The difference between the lower switchboard costs of the combined plant and the replaced ones must pay for the transmission to the main distribution centers, the investment in the unused part of the small plant and installation, less salvage, and for the investment in and operation of any additional substation or distribution apparatus required.

The question many municipalities, manufacturers and other consumers face is, whether they shall build their own electric plant or purchase arc lighting and current for general service. This matter should be decided upon the cost and service basis, but these matters are perhaps more frequently determined by guessing than by engineering and business methods. Many municipalities decide to purchase or build without knowing which is advisable and will spend thousands of dollars building or lose hundreds of dollars in operation rather than pay a small engineering fee to find out what should be done. There are cases where water, light, ice and cold storage, garbage incinerators, sewage disposal and other municipal departments have separate plants operating at a loss while the plants if combined or properly designed would earn a respectable profit. There are also cases where current can be purchased for less than it is actually costing to generate it and where extremely poor municipal service exists years after the same private service would not be tolerated. Let us consider the principal factors in the above paragraph.

Service. Few small municipalities consider service or make lighting contracts properly covering this subject. For arc lighting the nominal candle power is generally stated, the kind of current given and sometimes the watts consumed at lamps are stated but seldom, if ever, checked. The illumination is in perhaps 90 per cent of the contracts not even mentioned. All kinds of lamps and illuminations are frequently considered equal in cost comparisons. An ample reduction for outs is generally included when lighting is purchased, but seldom considered in figuring comparative costs from plants. In street lighting practically continuous illumination of proper intensity is the important item in comparisons or contracts. An ideal illumination would give uniform intensity at all places. It is necessary, however, in practice to have distributed lighting units which do not meet ideal conditions although attempting to come as close as possible to them. This involves the mean lower hemispherical candle-power and its distribution, in determining illumination at all points between consecutive lamps. Generally the illumination near the lamps is many times that half way between lamps, and lamps which have practically the same mean lower hemispherical candle-power do not give the same street illumination.

For lighting and power the limits of voltage variation, continuity of service and systems best suited to the requirements should be selected.

Cost. The question of cost is always considered and generally in dollars per arc lamp per year and cents per kw-hr. for other purposes. The question of costs seems at first view an easy matter which many municipalities and private concerns undertake to determine without engineering assistance. The usual proceeding is to inquire at surrounding plants the costs of plant and current. Sometimes costs from plants operating under similar conditions are considered and sometimes not, but in many cases any neighboring plant is too frequently taken as furnishing sufficiently accurate data for starting projects involving the expense of considerable sums and chances for loss in each year's operations. At this time the general opinions of many people are sought including the sales agents who volunteer favorable data. This method cannot possibly be advised by any one who is familiar with this question, and the experienced business man will say the risk is great enough even with the best engineering experience and study of conditions. Central station facts and factors may be of general assistance provided all the conditions are similar. To illustrate this we may first mention briefly some of the principal items of and conditions which affect the cost of power and then consider how much dependence can be placed on cost information generally furnished by any one in a power plant. This will show that a complete engineering investigation only will show what may reasonably be expected from plants and that this investigation should be made before considering either building a plant or purchasing power.

To show the impossibility of determining costs from incomplete data on other plants I give a list of prices paid in various cities for lighting.

Place	Number of lamps	Contract life years	Watts per lamp	Cost per lamp
Toledo, O.	2000	10	320	$45.00
Buffalo, N. Y.	700	5	320	52.00
Bridgeport, Ct.	645	1	320	73.00
Washington, D. C.	——	3	320	85.00
Rockland, Me.	118	7½	320	85.00
Wooster, Mass.	873	1	320	91.25
Syracuse, N. Y.	1500	5	320	68.00
Poughkeepsie, N. Y.	373	3	320	80.00
Chillicothe, O.	200	10	320	70.00
Newport, R. I.	165	7	320	104.25
Fall River, Mass.	862	5	320	91.25
Lancaster, Pa.	445	5	320	80.00
Harrisburg, Pa.	584	3	320	68.00
Reading, Pa.	700	5	320	67.50
Washington, Pa.	40	5	320	70.00
Philadelphia, Pa.	13258	——	——	94.63
Boston, Mass.	——	5	500	103.54

ITEMS AND CONDITIONS AFFECTING COST

Installation Cost. Fixed charges on investment, interest, depreciation, taxes, insurance.

Operation Cost. Operating plant and distribution, labor and material, fuel, oil, supplies, maintenance, miscellaneous.

General Expenses. Legal, office, management, collections, bad accounts, accidents, extraordinary.

Source of Power. Steam, water, gas, etc., or a combination of these.

Individual Light Plant or Combined with Water Works and other Departments.

Line and Distribution Losses.

The System, Uses and Size of Plant.

Minute variations in *local conditions* effect cost of erection and operation of engineering works and these costs fluctuate from year to year with business and other conditions. Erection and reproduction costs vary, unit costs of similar work done at the same or different times may be different. There is enormous difference in the *operating costs* of different plants and especially in small private and municipal plants.

Dependance Upon Data. No data can be of value without a thorough investigation of all the factors and accounting methods used in arriving at the figures. Complete and standard methods of accounting are used by few municipal and small private lighting concerns. For street railways the Interstate Commerce Commission has formulated some good systems, but the application of similar ones are needed to lighting concerns. It is remarkable how little is known about the real cost of lighting and power from small stations and results are frequently stated that are impossible. In the past, depreciation has been neglected perhaps more often than any other item, although interest on the investment is not considered on some municipal plants also and maintenances is in some cases greatly neglected.

After proper and uniform accounting is secured all the items given above under general conditions affecting costs and other factors, should be considered in making comparisons. The difference between operating and *total costs* should be properly understood. I have known cases where plant operation was taken as the total power costs when the remaining items would almost double the figure.

In comparing arc light costs the following items should receive attention:

Outs. Few lamps burn the full scheduled yearly hours. The fewer hours lamps are out the better the service. The reduction of outs to a low figure means additional expense for inspection, repairing, cleaning and spare machinery and supplies, etc. In large cities there is generally a deduction for outs from the price paid private plants for lights. In small towns generally there is a small or no deduction. In municipal lighting plants there is generally no deduction. Where there is a difference in outs there is then a difference in service which should be properly considered in comparative costs, for the better service costs more to furnish. Numerous methods of figuring deductions have been used, but no one can yet be considered a standard. Generally, however, the deduction is based upon price paid per lamp hour and total deduction found by multiplying this by the outs in lamp hours. In cases no deduction is made unless the lamp has been out more than one hour. In other cases the outs before midnight are charged at double the price paid per lamp hour. And when individual lamps are out three hours they are considered as out the entire night. There are also additional penalties when a whole circuit is out.

Reduced Illumination. Lamps operated at less than normal current or watts will give considerably less illumination with a reduction in cost due principally to saving in energy and carbons consumed and trimming. In some few places there is a reduction in price to cover this. One installation provides as follows: ¼ cent per hour reduction for each 5 per cent reduction from normal amperes or watts. When the reduction is greater than 15 per cent the lamp is considered out.

Recording instruments will show current and watts during each night's operation.

Tax on Poles. There are few places where there is not a pole tax on private installations. This varies in different cities up to $1.00 per pole and guy stub. Municipal plants do not, however, charge themselves, although the same installation by private concerns would mean an income to the city. This tax should properly be considered in private and municipal cost comparisons as it depends entirely upon local conditions.

Insurance. Fire, accident and liability, boiler and other insurance varies for different installations and therefore affects costs. The amount and kinds of insurance should be considered in comparisons as they require proper construction, suitable safety devices, and protect against poor and dangerous maintenance.

Borough and County Taxes. There is a wide variation in taxes which fluctuate from year to year and should be determined for the specific case in question.

Insurance and taxes are frequently figured at 2 per cent on investment which may be quite inaccurate. In this district taxes run from 6 to 26 mills and insurance from nothing to perhaps the highest rates in the world. Some municipal plants pay no taxes while private plants would bring this income to the borough.

Federal Tax. Large private or combined plants pay a federal tax on earnings over $5,000. Combined or larger plants must bear this increased burden over small ones.

Use of Poles. Municipal distribution systems frequently have the right to use part of other private company's distribution systems free of charge. As this is considered as part payment for right of way private plants doing municipal lighting should also have this right, reducing cost and number of pole lines.

Free Lighting. Private plants frequently furnish free lighting to city buildings and in these cases the cost of this item must be considered as increasing the cost of lighting.

In considering competition between private, combined and municipal plants there are also other costs which will be different.

Telephone Service. Municipal plants generally have reduced or free rates which private plants do not obtain. We believe this should also be treated in the same way as free poles or part of poles.

Franchises and Rights. Cost of franchises is quite different in different places and is more for private than for municipal rights. Time and money spent in this way increases the investment upon which a reasonable profit must be made. The greater the duration of franchises the less this yearly cost will be.

Bonds. Municipal bonds generally sell at a better price and have a lower interest rate than private bonds. Which means promotion, financing and operation may be less than in private plants.

Operation and Labor. It is not infrequent that the class of operatives in municipal plants are less efficient than in private plants which means higher labor costs.

Management. In some states municipal plants are managed by Boards of Public Service or paid councilmen and mayor and a part of this expense is properly chargeable to the light plant. In other states the unpaid city councils perform this duty free of charge.

Extraordinary. After all current expenses, fixed charges and depreciation are determined there are extraordinary and unforeseen expenses for every plant due to accidents, lightning, cyclones or heavy storms, explosions, great conflagrations, acts of strikers, etc., the cost of which is impossible to predetermine, but which exist, however, and reserve funds are frequently provided in private plants for such emergencies. Municipalities, however, do not provide for such circumstances, but appropriate funds to take care of trouble when it occurs. But these items certainly increase the cost of manufacture and should be allowed for.

Profits. Investors in private plants are entitled to a reasonable profit over and above the usual interest rates depending upon the risk incurred. The shorter the contract the greater is the risk. Municipal plants frequently claim small profits or eliminate them entirely trusting that exceptional expenses will not be incurred and knowing that the city can easily provide them when necessary.

Depreciation has been overlooked at times because its effects are only apparent after intervals of several years while profit and loss are determined yearly. If earnings were determined daily expenses that are paid say monthly might similarly be neglected for a time. This would mean large daily earnings for sometime and then a large daily loss until the debt was removed. Again if profit and loss were determined every 50 years depreciation and extraordinary expenses would undoubtedly not be forgotten and fat and lean years would be averaged so as to give a more uniform rate of profit. There would then be no distinction between maintenance and depreciation. In declaring yearly profit and loss it is necessary to consider these and provide for expenses that must be met at more than yearly periods by putting aside for the future needs part of each year's earnings.

Maintenance. This is the current repairs and detail replacements of parts that deteriorate rapidly and must be taken care of frequently in order to keep the plant in operation. This is an operating expense included in the yearly expenditures. There is good and poor maintenance depending upon whether the plant is kept in the best operating condition or otherwise. But after a number of years generally it is advisable, or necessary, to replace a complete machine or the entire installation and repairs or detail replacements will not suffice to render the further operation economical or even possible. This condition is due to depreciation, and as it may not be encountered for a number of years after operation has begun, it is, therefore, not included in yearly expenditures.

Depreciation is a diminution of value due to wear and tear, time, decrepitude, obsolescence, inadequacy, etc. Decrepitude is a gradual wearing out from age and use and ending of the useful operative life. This occurs when operation, maintenance and fixed charges on new unit is less than operation and maintenance of the old unit. It can not be overcome by current maintenance of the parts. Obsolescence is a reduction of the economical life due to advances in the art which limit the useful life before decrepitude, or when saving in the operation of new unit pays more than the fixed charges. Inadequacy, which may be considered as obsolescence, is the discarding of serviceable parts or complete installations on account of growth of business, combining plants, new laws or ordinances causing changes for esthetic or other reasons, old units not of right kind or size, and substituting underground for overhead construction. Short life contracts and franchise may require depreciation based upon their life.

Depreciation is generally a large item in costs of electric plants and it is taken care of by depreciation or amortization funds. The yearly depreciation is not uniform but varies at different periods during life. This is a broad question of itself and can not be covered by this paper, but the figures given are for a uniform percentage depreciation for each year. It is figured on the straight line basis as follows:

$$\text{Annual depreciation} = \frac{\text{wearing value}}{\text{years life}} = \frac{\text{first cost} - \text{salvage}}{\text{years life}}$$

Salvage equals junk or other value less cost of removal and sale or disposal and may have a negative value.

The useful life can only be determined by those thoroughly experienced with the apparatus used and conditions of service and the rapidity of advancement in the art, design and construction of machinery for the purpose. The higher the first cost the less the maintenance and the longer the useful life should be. The maintenance may have considerable effect on the decrepitude life.

Tables are compiled of the life of various parts of installations, but these must be used with caution as various conditions may change them considerably. Boiler installations may be used to illustrate this. Data from different tables published give an average life of 14 years, a minimum of 6 and a maximum of 25 years. The correct life depends upon the quality, kind, make, service and conditions. The water for example may change the life depending upon its deteriorating effects. The impurities, therefore, enter. A purifying filtering or heater system will change results. The thickness and quality of plates, type, load, kind of maintenance, hours of operation, whether feed water heater and regulator are used, etc., will also change these figures.

More accurate results will be had by considering all the factors mentioned above instead of taking the average life from tables, which generally cover only decrepitude.

It is advantageous in auditing and accounting to have the total or average percentage depreciation on the entire or important divisions of the installation. Parts of installations have quite different lives and it is necessary in arriving at a reliable figure to consider the life of component parts and their total cost installed. The following shows probable decrepitude life of parts of a definite distribution system.

	Years
Poles—Cedar 35 ft., 6 in., tops in earth untreated	12
Cross arms, yellow pine, 6-pin, untreated	7
Pins, locust untreated	6
Insulators, porcelain	12–15
Hardware, galvanized	8–15
Cut outs, porcelain	12
Lightning arresters	6–8
Copper wire (weatherproof 10, sulphur atmosphere 5)	20
Guy wire	8
Mast arms, heavy	14
Arc lamps	8
Arc cut outs	8
Miscellaneous	

The items in this table vary with conditions. If poles are treated or set in concrete their life and cost is increased. If set in stone, concrete sidewalks, etc., first cost is greater. The life of some other kinds of arms and treated arms is also longer.

The life of some parts may influence the life of others. If a pole for example must be removed when the cross arms are in rather poor condition, although serviceable, it is probable that new ones would be put up. It is, therefore, necessary to consider the life of units and also the various parts composing this unit. Separate units and the complete installation should then be considered in finding the percentage for whole installation.

The data can be conveniently tabulated using the following items. Parts having same life may be grouped together.

Items	Installed date	Useful life, years	New cost $	Salvage $	Wearing value $	Yearly depreciation $	Yearly depreciation per cent
Totals............							

$$\text{Average percentage depreciation} = \frac{\text{yearly depreciation (total)}}{\text{new cost (total)}}$$

I believe I have mentioned all the factors that generally enter in the above situation and have shown that conditions affect costs to such an extent that no two plants are actually operated under the same conditions. Each case must be considered and some special factors not generally found may then be developed.

Purchasers of light and power should realize that any special requirements such as pole tax, rigid deductions for outs or reduced illumination, severe service and regulation limits, free lighting or franchise taxes and rights-of-way charges mean an increase in cost of producing and therefore that the minimum rate charges must be raised to include these items.

PLANT DATA

Below are given some data on a combined municipal water and light plant which has given excellent results with the systems employed. The employees are few in number and efficient. The engineer and superintendent, to whom we wish to give credit for furnishing data and assistance, is capable and energetic and it is largely to his efforts that the plant makes such a creditable showing.

The data are for a steam-driven plant which is located on the Allegheny River Bank, and which serves a population of 8150 people. There are 1400 water consumers and water is pumped from ten 12-in. wells into city mains at 85 lb. pressure. The daily consumption is about 1¾ million gallons per day and the very approximate cost is 3¾ cents per 1000 gallons. The pumps now in operation were installed in 1886 so that they have had 25 years' service.

The electric plant furnishes arc lighting and 24-hour constant potential service to 350 paying consumers. No income is received from public buildings. The constant potential system is alternating current 1100 to 110 volts service; maximum plant capacity, 310 kw.

INVESTMENT

Real estate, building	$ 23.00	per kw.
Machinery and boilers, etc	61.00	"
Distribution system	58.00	"
Total	$142.00	"

Operation and general including everything except distribution	1.53	cents	per	kw-hr.	— 66	per cent
Depreciation 5¾ per cent	0.46	"	"	"	— 20	"
Interest 6 per cent	0.31	"	"	"	— 14	"
Total	2.30	"	"	"	—100	"

This does not include profit, exceptional expense and distribution costs, and shows depreciation amounts to 20 per cent of total cost even with very conservative figures.

Arc Lighting. The direct-current series system is installed and operates 100, 6.6-ampere enclosed arc lamps. The plant installation consists of one steam engine belted to two arc generators of 50 lamps capacity each, switchboard and appurtenances.

The investment is as follows:

Land, building	$ 36.00	per lamp
Machinery and boilers, etc	75.00	" "
Distribution system	64.00	" "
Total	$175.00	" "

A convenient method of showing the items and depreciation in this case is given below. Here the cost of current supplied to the arc circuit from the switchboard is determined first and the cost includes no profit and exceptional expenses. These figures are based upon 4000 hours service, 495 watts per lamp and 10 per cent line loss.

	Total cost	Without depr.	Without interest and depr.
Current at 2.3 cents kw-hr.	$50.14	$40.11	$33.43
Trimming	2.10	2.10	2.10
Carbons	1.00	1.00	1.00
Globes	0.75	0.75	0.75
Lamp repairs	0.60	0.60	0.60
Inspection and maintenance, tree trimming	0.15	0.15	0.15
Pole tax, and right of way, 50 cents each	0.68	0.68	0.68
Taxes, 6 mills on $42.00	0.26	0.26	0.26
Interest 6 per cent on $64.00	3.84	3.84	——
Depreciation 8½ per cent on $64.00	5.44	——	——
Outs reduction of candle power	——	——	——
Profit	——	——	——
	$64.96	$49.49	$38.97

Depreciation	$15.47	per lamp per year.
Interest	10.52	" " " "
Depreciation and interest	25.99	" " " "
Power plant labor	8.85	" " " "
" " fuel	16.64	" " " "
" " supplies	5.20	" " " "

The total appropriation is less than $40 per lamp per year.
No funds are provided for interest, depreciation or profit.

These figures do not include a deduction for outs and low candle-power as these are not enforced on the plant. Nor do they include profit or reserve fund to meet exceptional expenses. The taxes are rather low at 6 mills on two-thirds valuation. The poles tax is at 50 cents per pole the price charged other companies. The inspection, maintenance and tree trimming are very low as part of this real cost is included under trimming lamps and can not be separated. The total insurance runs about $110 per year on the combined water and light plant. The telephone service is obtained at a very low figure. The bonds pay 4 per cent. The labor is very economical, two men per shift operate the combined power plant on 12 hour shifts. The superintendent and engineer divides his time between water, incandescent and arc lighting systems. The depreciation is conservative.

APPROXIMATE VALUE OF SPECIAL ITEMS

It is interesting to know how much the items not entering in above detail figure amount to in other cases where they apply.

A conservative estimate of cost of *outs* when there is such a deduction in contracts may be figured for small plants on the basis of one day out in every two months operation or at about 1⅔ per cent. At the rate paid per lamp per hour this would be approximately $1.00 per lamp per year.

The *profit* should be for a long term franchise and contract at least 6 per cent in order to attract investors to such undertakings.

The *reserve* fund should probably be at least ½ per cent on the investment.

Free lighting will average for small plants, 50 16-candle power lamps for which the yearly cost will be at 4 cents per kw-hr. and 1000 hours burning about $1.10 per lamp per year.

Emergency connections vary in cost so much that it is difficult to give a figure.

Normal telephone rates would be approximately $.50 per lamp per year higher than actually paid at this plant.

An Address delivered at the 28th Annual Convention of the American Institute of Electrical Engineers, Chicago, Ill., June 27, 1911.

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ELECTRICAL ENGINEERS AND THE PUBLIC

President's Address

BY DUGALD C. JACKSON

Members of the American Institute of Electrical Engineers are pleased to refer to electrical engineering as a Profession, and to the Institute itself as a Professional Society. When this occurs as a thoughtless repetition of fine sounding words, it has little meaning, since mere repetition of an alleged truth does not make it a real truth, and it can be established as a real truth only by tracing it to some adequate foundation. But when those statements arise from a ripe understanding that the word profession means more than a mere organized vocation for earning one's bread, it has a high and commendable meaning. The word profession "implies professed attainments in special knowledge, as distinguished from mere skill; a practical dealing with affairs, as distinguished from mere study or investigation; and an application of such knowledge to uses for others, as a vocation, as distinguished from its pursuit for one's own purposes." This sets the professional man in a position which demands from him an attitude of service and of leadership. He must have a masterly knowledge, in addition to skill in a vocation. He must deal practically in the affairs or needs of men. His duties must be performed with a touch of disinterested spirit in addition to the vocational spirit of earning his livelihood. Such men have a duty to the public; and in the performance of that duty they must exert their influence on that thought and practice of the day which affects the welfare and progress of the nation. We as electrical engineers cannot escape that duty in case we wish to maintain the professional character of our occupation.

It may be retorted that questions relating to the welfare and progress of the nation are matters of economics and sociology, and not of engineering. The affirmation contained in this retort I will admit, but the negation I deny.

The theory of modern economics is built up under the influences produced by the introduction of steam power, with its potent agencies comprised in the steam railroad, ocean navigation, and the use of steam power in industrial operations. These agencies are the creatures of engineers. Watt, Stephenson, Fulton, Ericsson, Boulton, Arkwright, Nasmyth, Bessemer, Siemens, Corliss, Holley and the other fathers of our modern industrial economic conditions were engineers; and it would be folly to deny to the parents an interest in their offspring, and equally folly to assert that the further developments of economic theory are not largely dependent on those industrial changes which are continually produced by the inventive activities of the great body of engineers. When I speak of industrial operations or industrial conditions, it must be understood that I include among industrial affairs the great means for transportation and intercommunication which are comprised in railways, telegraphs and telephones, in addition to the manufacture and distribution of products which involve the application of mechanical power as distinguished from animal power, and the manufacture, accompanied by distribution by pipe or wire, of the media for providing illumination and power. The engineers have precipitated these affairs on the world by their inventions; these affairs are in a large measure the support of the engineering profession; and it is the duty of engineers to do their share in moulding their various economic creatures so that the creatures may reach the greatest practicable usefulness to society. In fact it would show a cowardly weakness to suggest that this duty should be avoided by men who are essentially responsible, as the engineers are, for the existing conditions. Theologians and physicians can practice their professions aloof from the ordinary affairs of the world, but the engineers associated with industrial events cannot. Moreover, such an avoidance of their duty by the engineers, even if avoidance of responsibility were possible, would be particularly unfortunate in view of the fact that the professed economists and sociologists apparently do not yet hold themselves subject to all the requirements of professional men, but still interpret their duties as being more confined to the field of study and investigation than to applying their knowledge to practical affairs.

It may again be retorted that the tenets which I am advocating will lead engineers out of a professional spirit and into "commercialism". It is worth while to pause here to reflect on that point. The word "commercialism" strictly means the characteristics of business or commercial life, but custom has made it applicable to any undue predominance of commercial ideas in a nation or community, and it has thereby come to infer a willingness to establish the strife for money in a position of precedence over reason and righteousness.

It has been alleged that learning loses of its dignity by becoming fashionable. It has also been alleged that learning loses of its dignity by becoming useful. Of the latter, at least, experience has proved the contrary,—happily for engineers who are proud of their profession, for engineering is necessarily an embodiment of the useful application of knowledge and learning. Engineering, relating, as it does, to the application of the powers of nature to useful purposes, must necessarily bring its followers into intimate contact with commercial affairs in an age when, as in ours, the industries dominate commerce, and the abatement of war has reduced the importance of military engineering. The tenets which I advocate do not tend to entangle the engineers in the depths of "commercialism" with which they may come in contact; but, on the contrary, those tenets propose that engineers should safeguard and nourish their professional spirit by assuming a part in public affairs in a spirit of disinterest, for the purpose of guiding the useful applications of natural forces to the greatest practicable service to society. A true engineer is a devoted follower after truth. He differs diametrically from the devotees of pure "commercialism", who are strictly opportunists. He also differs from pure idealists, who are often notable for refusing to accept any advance unless it wholly meets their personal ideals. The spirit of the engineer rejoices in obtaining any move toward the truth, but is always seeking farther advance. This characteristic spirit has been manifested in men of great achievement in many walks of life. It is a part of the life of such men as Martin Luther, Gladstone and Lincoln.

Those who accept even in part the usual evolutionary doctrines which are summed up by Herbert Spencer in his view that progress occurs by successive differentiations and integrations producing development from the homogeneous to definite, coherent heterogeneity, will assent to the proposition that the modern giant corporation follows in the wake of the one-man business and the simple partnership in response to an inextinguishable natural law. This is a case of natural selection.

The progress of corporation development cannot be prevented. It is one of the manifestations accompanying improved means of speedy transportation and inter-communication. Of the influence of the latter agencies, a learned and distinguished historian says, "Of all inventions, the alphabet and the printing press alone excepted, those inventions which abridge distance have done most for the civilization of our species. Every improvement of the means of locomotion benefits mankind morally and intellectually as well as materially, * * *." The possibility of, and indeed a necessity for, great corporate organizations came in the train of leading improvements in the means of locomotion and other beneficial inventions which abridge distance and subjugate time. Men of this age do not desire to relinquish the benefits of the improvements. We must, therefore, adjust our mental attitude to dealing properly with the situation; and in making the adjustment we must return to the old and approved recognition that a misdeed is a personal thing, and remember that responsibility for it cannot be shifted from the personality of the man in responsibility to an impersonal aggregation entitled a corporation which he manages. In early days when English kings had great prerogatives in the government, and the doctrine of divine right, associated with the doctrine that the king can do no wrong, were still extant, the king was nevertheless limited to an administration of the affairs of the realm conducted, history tells us, in accordance with the laws, and, in case he broke those laws, his advisers and agents were held responsible, and they were made personally answerable to the courts. History also indicates that this personal answerability of the advisers and agents had a tremendous influence on the conduct of government and its relations to the public. In building up our industrial structure we must not overlook the plain guide board of history, and personal answerability must be established. But if we must establish personal answerability to the public, we must also establish fair and generous dealing by the public.

The building up of a great industrial nation in an honorable state of civilization is subject to many hazards,—an error may cause injury to the structure that takes years or even decades to eradicate. It is, therefore, desirable to go cautiously and utilize the mature reflection of straight-thinking men who will give their thought to the subject. The forward route is untested, and real progress can be made only by judiciously combining teachings from the records of yesterday with experience of to-day to make a working theory for to-morrow. It has been suggested that a theorist should be defined as a man who thinks he may learn to swim by sitting on the bank and watching a frog. Doubtless, there are many such men in the world, but they are not theorists. The definition is as inaccurate as defining a black object as an object without color. Such men are only inexperienced, superficial or foolish. Theory, as the word is used by engineers, means a working hypothesis founded on all known facts and experience, which may be used to guide progress beyond the margin of past experience. Every successful, progressive man is a constant user of theory in this proper sense of the term. Every progressive step is made according to a theory of the man responsible for the move. Theory is not antagonistic to practice but is founded on experience and is a guide to progress. Custom should be followed only when it has reason to support it. In the juncture now before us we must utilize the best theories of the corporation relations and the rights of persons and property, and cautiously extend our practices accordingly. No body of men are better equipped for this sound and scientific procedure than a body of professional engineers; and few others are so fully and adequately trained for such procedure as engineers, for the reason that this procedure is in accordance with the every-day steps of their business life. Moreover, the engineers of experience are well adapted to grapple with the mighty problems of a new age, for the reason that an efficient engineer must associate audacity and sobriety in his spirit.

If my premises are tenable, and I believe them to be incontestible, the engineers have a special duty, as professional men who are trained and experienced in straight thinking, to use their influence for the establishment and support of right and reason in the dealings between the public and the public service corporations. The problems surrounding the public service companies in American cities, and their relations to the citizens, should receive particular attention by members of our Institute, for those problems and those relations have been largely brought to their present importance and prominence through the activities of electrical engineers.

The public service corporations are the natural outcome of the demand of the civilized world for efficient and rapid transportation and intercommunication, and the concurrent need as communities become immersed in peaceful industrial pursuits for ample and conveniently provided supplies of water, gas and electric power. They compose a comparatively new and mighty force in the social organism and the organism must be adapted to efficiently utilize this force, but the force must be prevented from dominating or warping the organism. There is no danger of the public service corporations becoming despots as some people seem to fear, provided they are put under proper restraints, but society cannot afford to make restraints which of themselves are unnecessary or unfair. These corporations serve a beneficial end in our life, and their rights are as well founded and should be as well secured and held sacred as the rights of any citizens who are individually or collectively bent on any proper business pursuits.

Some people seem to believe that all public service corporation men are either wicked or are liars or thieves. This has as little foundation in fact as a belief that all men in Spain carry mandolins or that Spanish women always wear mantillas. If such unjust, superficial and improper opinions are to have influence in this nation, then only misfortune and woe can be the outcome. It is necessary for all men trained in straight thinking to combat such folly and to cry out for fair dealing, one with the other, as between the public service corporations and the public which they are established to serve. No engineer does his duty who does not stand with fidelity for equally square treatment FOR as BY these corporations. These corporations are not here as vampires on society, but are here to serve the needs of the people in a reasonable and business-like way; and their proper objects cannot be accomplished unless thay are treated with reason and established in confidence. They obtain their income from serving the public, and they cannot give generous service unless they are granted generous opportunities. When under reasonable restraints and supervision, as by properly constituted public commissions, they are more quickly responsive to public sentiment than could reasonably be expected of any publicly owned business organization of equal magnitude which could exist under our political conditions, and their usefulness is proved beyond contradiction. Perhaps no man is more likely to observe these things than one whose professional practice, like that which has come to me, makes him retained adviser in some instances to public service companies and in other instances to governments or municipalities, for he has to study fairness to each class of clients in all he does.

A barrier of distrust which exists between these servitors of the people and the people which they serve is presumably due, on the one hand, to a memory by the public of misdeeds which were perpetrated before recent demands for reform brought about the establishment of adequate public supervision in prominent centers, and to a fear of the repetition of misdeeds where supervision and publicity have not yet been prescribed; and, on the other hand, to a certain reluctance by corporation managers to exhibit full and convincing frankness for fear that such frankness may be made the opportunity by unscrupulous politicians or persons with interested motives to crowd them to the verge of insolvency. These particular conditions of distrust could be obviated by means of the public itself owning the public service properties and operating them in its own interest, but this is a drastic and undesirable alternative. Any fair-minded man of extended business experience who will study with unbiased intention the details of public ownership and public trading in the venerable and stable cities and states of continental Europe must be impressed with the reality that our inexpert and shifting governmental bodies are wholly unadapted to cope with such responsibilities, or to make an economic success equal on the average to that now accomplished by the privately managed service companies, whether the measure of success be taken on the basis of service provided for a unit of payment or on any other reasonable basis of comparison.

If the public could feel sure of the ingenuousness of corporation statements and statistics, and the corporations could be protected from unfair attacks made by ignorant, although, in many instances, educated, persons or persons with ulterior motives, the barrier of distrust to which I have referred would be dissipated as dampness is dissipated by the rays of the sun; but this cure requires a long step forward in the average line of progress, for it demands a supervision of the companies which imposes on them exact and ingenuous bookkeeping associated with the presentation to the public of accurate and luminous statements of their business, and it equally demands that the public shall be required to yield justice to the companies with the same ample fullness as individuals seek it for themselves. A progressive step of this nature is always accomplished slowly and hesitatingly. I have observed in Macaulay's writings a paragraph which is graphic in illustration of our present situation. "Everywhere," he says, "there is a class of men who cling with fondness to whatever is ancient, and who, even when convinced by overpowering reasons that innovation would be beneficial, consent to it with many misgivings and forebodings. We find also everywhere another class of men, sanguine in hope, bold in speculation, always pressing forward, quick to discern the imperfections of whatever exists, disposed to think lightly of the risks and inconveniences which attend improvements, and disposed to give every change credit for being an improvement. In the sentiments of both classes there is something to approve. But of both, the best specimens will be found not far from the common frontier. The extreme section of one class consists of bigoted dotards; the extreme section of the other consists of shallow and reckless empirics."

The public, misled or annoyed by the reluctance of some honest but overcautious managements to make frank public statements of financial results and present convincing statistics of operation, enraged by the acts of a few adventurers who from time to time have secured a speculative hold in the public service field, and enticed by the arguments of individuals with ulterior motives, are likely to follow the radical leadership of demagogues or of honest but false empirics. This is a danger which seriously exists in states where no public supervision of the service companies is provided, and also in a lesser degree in states where such supervision has been established. The danger must be rolled back by the exertions of fair-minded and right-thinking men. A serious menace to the welfare of the nation would be caused if unfair dealing toward the public service companies were established as a policy. A scrupulously frank and honest dealing with the public by the companies should be insisted on, but the public must be taught the importance of dealing on its part with an equally scrupulous fairness and a well-balanced generosity. It is here that I say lies a duty of electrical engineers to the public. It is to give of their time and brain to convincingly establish the facts (the *facts*, I repeat) which the public do not understand in regard to the business of the public service companies, to indicate the means for rightly treating these new influences which we and our fellow engineers have been creating by our works, and to aid in establishing measures which will favor and sustain mutual confidence and fair dealing between them and the public. This is an obscure and difficult problem on account of its touching the edge of men's ambitions and men's passions, and it seems at times to possess the opacity and insolubility of a mill-stone; but looking persistently and with care into what appears to be a mill-stone, not infrequently proves it to be composed of reasonably transparent material. The members of our Institute should take somewhat to themselves as professional men this obscure and difficult problem, and aid in its solution as a matter of their duty to the public.

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THE USE OF POWER-LIMITING REACTANCES WITH LARGE TURBO-ALTERNATORS.

BY R. F. SCHUCHARDT AND E. O. SCHWEITZER

INTRODUCTION

In large electric power systems the maintenance of a very high degree of reliability, that is, continuity and uniformity of service, must be the constant aim and is one of the principal problems of the engineer. While the problems during the earlier years of central station work often appeared very difficult, the advent of the large capacity, high-speed turbo-generators coupled to systems containing hundreds of miles of transmission lines, made them much more complex and they took on a far more serious aspect.

The question most actively before some of the larger electric power companies at the present time is that of limiting the amount of energy which can flow into a fault. The solution in some instances of present turbo-generator installations will probably be the installation of current limiting reactances. It is the purpose of this paper to present some of the data obtained during a long series of unusual tests made during February, March and April of this year, on such reactances in conjunction with a large turbo-generator and to offer a few conclusions based on the results.

EVOLUTION OF ENGINEERING IN THE SYSTEM OF A LARGE CITY

In tracing the various steps in the evolution of the engineering with respect to provisions for safe-guarding the generating apparatus, the writers naturally cite the experience of the system with which they are most familiar, namely, that of the Commonwealth Edison Company and its predecessor companies. The troubles of the stations of the early years are quite well known and in the light of present knowledge were comparatively simple. No time will be taken in this paper for their consideration. This applies to stations down to and including the time of slow-speed alternators direct coupled to reciprocating engines and feeding a transmission system of some considerable size. It was not until the introduction of the high-speed turbo-alternators that serious troubles were experienced which indicated that these later units had characteristics quite different from those of their engine-driven predecessors.

The experience in Chicago during the past eight years, that is, since the operation of the Fisk Street Station with its pioneer 5000-kw. turbo-generators was begun, showed an increasing severity in the disturbances (due to apparatus and cable breakdowns) with the growth of the stations and, therefore, apparently due to the increase in generator capacity. This can perhaps be better appreciated when we remember that previous to October, 1903, the total capacity in high voltage alternators on the system of the then Chicago Edison Company amounted to 9800 kw., while in October, 1911, the total capacity of the three large stations will aggregate about 250,000 kw.

The original 5000-kw. generators at Fisk Street, of which there were four, had their neutrals grounded solidly. These were all 9000-volt six-pole machines operating at 500 rev. per min. The fifth unit to be installed was of larger capacity and, having four poles, operating at a speed of 750 rev. per min. It was found that with the neutral of this fifth unit closed to ground a comparatively heavy cross current flowed between it and the other units, and a neutral resistance of approximately 2½ ohms was installed on the new unit. This resistance incidentally served to limit the current which would flow into grounded apparatus or cable ("Y" pressure of the generators is 5200 volts). All additional units were, therefore, provided with neutral resistances and later the solid connections to ground of the four original units were removed. To further limit the current flowing into a single-phase fault, the neutral was closed on only one of the units operating on the system. With the continually increasing capacity the exact effect of these various changes could, of course, not be determined, as breakdowns in apparatus or in cable do not occur with great frequency and in most cases the conditions are so involved that the effects cannot be accurately analyzed. It is easily seen, though, that these various steps must have served to reduce the energy flowing into a single phase fault.

Disturbances were, however, still of sufficient severity occasionally to have a widespread effect and the system was, therefore, divided into sections so that a fault was reduced in severity and limited to one section, leaving the remainder of the system undisturbed. This was going back in part to the original method of operating this station, each unit initially having fed only its own lines independent of the other units. The maximum capacity now permitted on each section was set at 50,000 kw. Even with these precautions, however, severe disturbances occurred and especially at times when the generator armatures themselves developed faults. In the four years from 1906 to 1909 inclusive, there were seven generator burn-outs, all of which caused a temporary shut-down of part or all of the substation apparatus on the section to which the particular generator was connected. The storage batteries, of course, meanwhile maintained the service in the direct-current districts. In practically all of these cases the armature end turns were torn loose and the windings were pretty well wrecked. It was then appreciated more strongly than ever before that a more rigid construction of the generator was necessary and the armatures were rewound with a new form of coil with a very much improved arrangement of end turns; also, one coil was laid in a slot instead of two, as in the former winding. The experience thus far apparently indicates that this improvement is satisfactory. With severe short circuits the switches continued occasionally to give considerable trouble and in one or two instances actually failed.

On the 20,000 volt system fed normally through two 5000-kw. transformers from the 9000-volt system which transformers originally had a reactance of approximately 2½ per cent, cable breakdowns in four instances caused disastrous results within the transformer, completely wrecking part of the winding.

NEED FOR INCREASED REACTANCE

The absolute necessity for reducing the current which can flow into a fault was now very clear. As this current is a function of the reactance of the circuit it was apparent that the reactance must be increased. The transformers were rewound in a manner to give an internal reactance of approximately 4½ per cent. An additional amount could be added externally. In the case of the generators the higher value of reactance could, of course, be taken care of in new designs. In new units of very large capacity it was thought best to divide the desired total reactance between the generator itself, winding it for comparatively low voltage, and an auto-transformer which would serve to step up the voltage to the required value. The major duty of withstanding the shocks caused by system disturbances, was thus placed on a device external to the generator. In the case of existing units the additional reactance could best be supplied by the use of external coils which would serve also as a buffer against potential risk and relieve the generator of excessive short circuit strains. The installation of an induction generator would have introduced numerous complications and was, therefore, not considered.

REACTANCES FOR TRANSFORMERS

For the transformers above mentioned, further additional reactance was provided in the form of external coils of approximately 4 per cent reactance (that is, designed to absorb 4 per cent of the "Y" voltage at full load current). These were connected in series on the primary or 9000 volt leads. They have now been in service nearly two years and during that time the transformers have successfully withstood a number of short circuits of a kind which previously had caused them to be wrecked.

REACTANCES FOR GENERATORS

In the case of the generators the installation of reactances presented a far more serious problem. There was a natural hesitancy at the beginning in installing apparatus on which so little definite knowledge was available and which required a considerable outlay of money for its installation. In order to house the coils at Fisk Street, for instance, an addition was required along the entire length of the switch house, while at Quarry Street where there are four 25-cycle units of 14,000-kw. capacity each, part of an excitation storage battery had to be moved and material structural changes made to provide the necessary room.

PURPOSE OF AND PREPARATION FOR TESTS

In view of the large investment required and the possible hazards that might result, it was deemed desirable to learn more about the actual behavior of the proposed coils and their effectiveness toward the desired results before proceeding with their installation and for this purpose an elaborate and very complete series of tests was conducted, using one of the 12,000-kw., 9000-volt, 25-cycle turbo-generators at the Fisk Street Station.

All conductors of this unit, that is, armature and field leads and all meter and control wires, were disconnected from their regular service and connected temporarily to points outside of the station. A section of the basement at the end of the building was partitioned off and the reactances were installed therein. A temporary structure was erected in the yard outside of the station building and in this were placed two oil switches, one for making the short circuit on the 12,000-kw. unit and the other for opening this short circuit. The very unusual opportunity offered for studying the action of oil switches was taken advantage of and a number of tests were made on such switches, the results of which are presented at this Convention in a paper by Mr. E. B. Merriam.

One end of a construction shop located in the yard about 50 ft. from the oil switch structure and from which a full view of the switches was had, was temporarily converted into a control center and in this were placed two oscillographs, terminal boards for the control and meter wiring, and suitable panels carrying the switches and meters. A telephone system was installed between this temporary control center and a convenient point in the turbine room and all the work to be done by the large number of attendants and observers was thoroughly organized so the tests could be made safely and expeditiously.

The points to be determined by the tests were the following:

1. The instantaneous short circuit current of turbo-generator without external reactance.
2. The instantaneous short circuit current of turbo-generator with an external reactance of 4 per cent.
3. The instantaneous short circuit current of turbo-generator with an external reactance of 6 per cent.
4. Duration of the transient phenomena incident to the short circuits under conditions 1, 2 and 3.
5. The effect on the generator of these short circuit currents.
6. The behavior of the reactance coils.
7. The effect of the installation of reactance coils on the stability of the system.

DESCRIPTION OF APPARATUS TESTED

The unit selected is turbo-generator No. 10 and is shown in Fig. 1. The generator has a "barrel coil" winding made up of 36 coils, four turns per coil, laid in 72 slots. The resistance of the armature per phase of the "Y" winding is 0.0244 ohms at 25 deg. cent. From calculations made to determine the armature impedance, it was found that this is approximately 2 per cent. This value, however, does not include consideration of transient constants and the effective reactance at time of short circuit is in excess of this value due to several causes chief of which is the rapid dying down of the field, as is clearly brought out in the data presented. The full load current is 770 amperes. Fig. 2 shows a view of the armature winding, the field being removed, and incidentally illustrates the new form of end turn construction.

FIG. 1

The field is of the indefinite pole, laminated core type. Its resistance is 0.238 ohms at 25 deg. cent. measured from the terminals at the collector rings. The full load excitation with unity power factor is approximately 400 amperes. Fig. 3 shows the field. The ends are shown covered with boiler plate. The winding can, therefore, not be seen except where it passes the air ducts.

A set of three reactance coils, one for each phase, was used. This is shown in Fig. 4 and was designed for a reactance voltage at 25 cycles of 312 per coil (6 per cent of the Y voltage) with a current of 770 amperes. Each coil has 76 turns of 1,000,000-cir. mil cable wound on a hollow concrete core having no iron in any part. The inner diameter of the turns is approximately 2 ft., 10 in., and the outer diameter about 4 ft. 3 in. The inner layer has 26 turns, the middle has 24, and the outer layer 26 turns. The vertical distance between turns is three in. and the horizontal distance between layers is $2\frac{1}{4}$ in. The diameter of the copper is approximately $1\frac{3}{16}$ in. The coils used in the tests have an outer layer of $\frac{1}{2}$-in. cord, as shown in the figure. This is for the purpose of preventing persons or materials coming in contact with the bare conductors. The total height of the coil structure is approximately eight ft., and the copper turns extend over about three-fourths of this height. By measurement the impedance of each coil at 25 cycles is 0.425 and the resistance 0.0075 ohms. The coils were installed six ft. between centers and anchored into the concrete floor and braced at the top by 6-in. by 6-in. oak beams, 14 ft. long. The clearance between copper of adjacent coils was 27 in.

Fig. 2

The connections were made as shown in Fig. 5.

Description of Tests

The short-circuiting switch was closed in all cases with the generator at full speed. A total of 167 short-circuit tests were thus made of which 88 were at full voltage, 38 at one-half to full voltage, and 41 at less than one-half voltage. With the exception of a few tests as noted in Table V and VI the neutral connection of the generator was solidly grounded throughout the series. In the case of the exceptions a 2½ ohm resistance (one of the regular neutral rheostats used at the station) was inserted in this neutral connection. Two oscillographs were used, as shown in Fig. 5, and records were obtained of various currents and pressures, as indicated below.

The initial tests were, for safety, made at low voltage and these were followed by a large number of tests under various conditions, the majority, as already stated, being at normal voltage. The principal data obtained are given below. The pressure traces of the oscillograms were obtained from the secondary of 200 watt potential transformers, ratios 100 to 1 and 120 to 1, (see Fig. 5), and the current traces from the secondaries of type S current transformers, the ratio being selected with reference to the probable primary current. To test the effect of stray field from the reactance coils upon the 120 to 1 current transformers used to get oscillograms of generator currents and

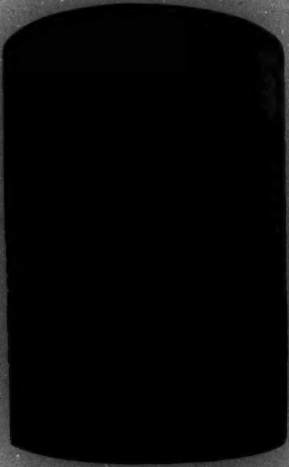


FIG. 3

which were placed about six feet from the reactances, a 400 to 1 current transformer was installed on the *A* phase of the armature leads on the turbine room floor at least 30 ft. from the reactances. Comparative oscillogram curves are shown taken from this transformer and the regular transformer. The first rush of current as shown by the two transformers checks closely, but considerable discrepancies exist in the current values during the later cycles as shown in Figs. 14 and 15. In all oscillograms except those shown in Figs. 6, 24 and 26, 400 to 1 current transformers were used instead of 120 to 1 current transformers for the traces of generator currents.

Unfortunately in mounting the oscillograms, special attention was not paid to arranging the two prints, where two oscillograms were taken at one time, so that simultaneous occurrences would appear in line. Because of the time limitation it was impossible to correct this before the illustrations had to be sent in for reproduction. However, the simultaneous sequence of events is so clearly shown that the occurrences can readily be studied with relation to each other. In all cases the sequence of events illustrated on oscillograms is from left to right and in the identification marked below the curves, the traces are read from top to bottom. In connection with the study of the various waves it should be stated that the absolute phase rotation of the system is in the direction C. B. A.

Fig. 4

Considerable data can be obtained from these oscillograms which are of great value and interest in the study of the charac-

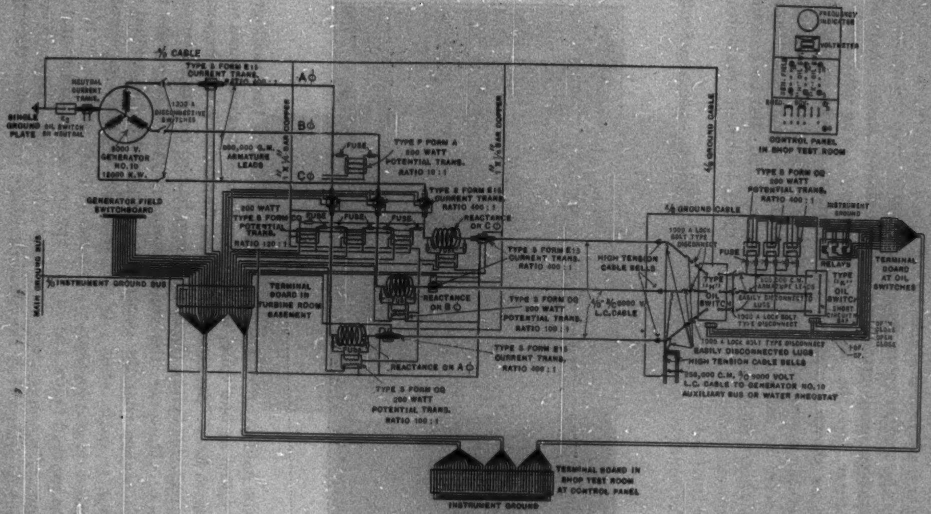
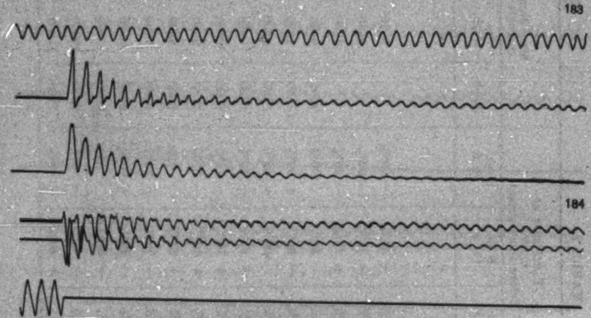

⅘ CABLE
TYPE 3 FORM E15 CURRENT TRANS. RATIO 100 : 1
AΦ
BΦ
CΦ
NEUTRAL CURRENT TRANS.
SINGLE GROUND PLATE
K2 OIL SWITCH ON NEUTRAL
1200 A DISCONNECTIVE SWITCHES
9000 V. GENERATOR NO. 10 12000 K.W.
800,000 C.M. ARMATURE LEADS
1" X ¼" BAR COPPER
FUSE
TYPE P FORM A 200 WATT POTENTIAL TRANS. RATIO 10 : 1
TYPE 3 FORM E15 CURRENT TRANS. RATIO 400 : 1
GENERATOR FIELD SWITCHBOARD
200 WATT TYPE 3 FORM OQ POTENTIAL TRANS. RATIO 120 : 1
REACTANCE ON C Φ
MAIN GROUND BUS
⅘ INSTRUMENT GROUND BUS
TERMINAL BOARD IN TURBINE ROOM BASEMENT
REACTANCE ON B Φ
REACTANCE ON A Φ
TYPE 3 FORM OQ 200 WATT POTENTIAL TRANS. RATIO 100 : 1
TYPE 3 FORM E15 CURRENT TRANS. RATIO 400 : 1
TYPE 3 FORM OQ 200 WATT POTENTIAL TRANS. RATIO 100 : 1
TYPE 3 FORM E15 CURRENT TRANS. RATIO 400 : 1
1" X ¼" BAR COPPER
4/0 GROUND CABLE
4/0 GROUND CABLE
HIGH TENSION CABLE BELLS
4/0 3/C 9000 V. L.C. CABLE
1000 A LOCK BOLT TYPE DISCONNECT
TYPE "H" OIL SWITCH
FUSE
800,000 C.M. ARMATURE LEADS
EASILY DISCONNECTED LUGS
1000 A LOCK BOLT TYPE DISCONNECT
TYPE 3 FORM OQ 200 WATT POTENTIAL TRANS. RATIO 400 : 1
INSTRUMENT GROUND
RELAYS
TYPE "K" OIL SWITCH
SHORT CIRCUIT BAR
TERMINAL BOARD AT OIL SWITCHES
OPEN
CLOSE
OPEN
CLOSE
TOP.
OP.
1000 A LOCK BOLT TYPE DISCONNECT
EASILY DISCONNECTED LUGS
HIGH TENSION CABLE BELLS
250,000 C.M. 3/C 9000 VOLT L.C. CABLE TO GENERATOR NO. 10 AUXILIARY BUS OR WATER RHEOSTAT
FREQUENCY INDICATOR
VOLTMETER
GEN. FIELD
OIL SW.
RHEO.
GOV.
CONTROL PANEL IN SHOP TEST ROOM
TERMINAL BOARD IN SHOP TEST ROOM AT CONTROL PANEL
INSTRUMENT GROUND

FIG. 5

teristics of turbo-generators of the type under test but the practical bearing of some of this data is somewhat remote and because of the extreme length to which this paper would otherwise have to be carried, considerable of it is omitted. Thus for instance, the value and characteristic of the field current under the various conditions comes in this class. This and other of the data open up a vast field for study and many of the questions in connection with them would of themselves and with the test data furnish sufficient material for a long paper. Many of the oscillograms contain a trace obtained from the field current and these traces show in a general way the action of the field.



Trace No. 1—Time reference wave from 25-cycle system.
2—*C* phase generator current; scale 20,100 amperes per in.
3—Generator field current; scale 3,300 amperes per in.
4—*A* phase generator current; scale 23,700 amperes per in.
5—*B* phase generator current; scale 28.200 amperes per in.
6—*A B* generator delta pressure; scale 33,000 volts per in.

FIG. 6.—Oscillograms of a three-phase short circuit with no external reactance at 3,000 volts generator delta pressure with steam on turbines

THE TESTS

1. THE INSTANTANEOUS SHORT CIRCUIT CURRENT WITHOUT EXTERNAL REACTANCE

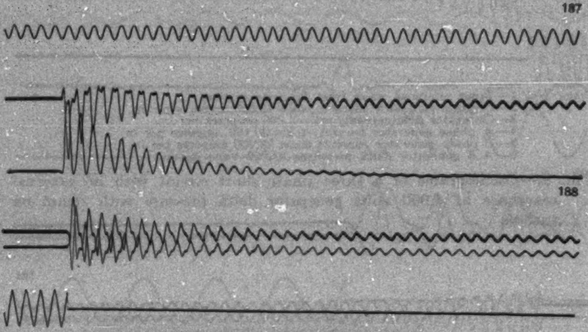
In order to determine as nearly as possible the exact effect of the reactances in limiting the energy flowing into a fault it was necessary to obtain data of turbo-generator characteristics without external coils. It was obviously unsafe to carry this to the limit of normal voltage but tests were made at voltages from

TABLE I.

Test No.	Oscillograms	Per cent external reactance	Oil switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph.	*B* ph.	*C* ph.	
54	137	0	H-3	3 φ	1000						1800	
55	139	0	"	"	1000						4550	
56	141 142	0	"	"	2000	+ 58%	— 41%	— 99%		5200	3100	
57	143 144	0	"	"	3000	+ 80%	— 11%	— 92%		9400	6100	
58	147 148	0	"	"	3000	— 99%	+ 57%	— 43%		7800	7800	
78	179 180	0	"	"	3000	+ 50%	— 50%	100%	7260	9400	6000	
79	181 182	0	"	"	3000	— 7%	— 89%	+ 82%	7100	7500	4000	
80	183 184	0	"	"	3000	— 48%	100%	+ 52%	6900	4700	6700	See Fig. 6.
81	185 186	0	"	"	3000	+ 74%	— 22%	— 95%	6700	9400	6400	Steam shut off just before short circuit.
82	187 188	0	"	"	3000	+ 94%	+ 18%	— 76%	6000	10000	8240	See Fig. 7
83	189 190	0	"	"	3000	— 98%	+ 66%	— 32%	5760	8940	9000	
84	191 192	0	"	"	4000	— 87%	+ 87%	0%	9230	8800	7600	
85	193 194	0	"	"	4000	— 33%	— 98%	+ 65%	9720	7700	7360	See Fig. 8
86	195 196	0	"	"	4000	— 39%	— 99%	+ 66%	9920	8800	8500	Steam shut off just before short circuit.
87	197 198	0	"	"	4000	+ 87%	— 87%	0%	9520	7460	9900	See Fig. 9
88	199 200	0	"	"	4000	+ 58%	— 41%	— 96%	9720	12200	8200	
89	201 202	0	"	"	4000	+ 99%	+ 40%	— 59%	7200	11850	11300	See Fig. 10

+ Represents increasing wave. — Represents decreasing wave.

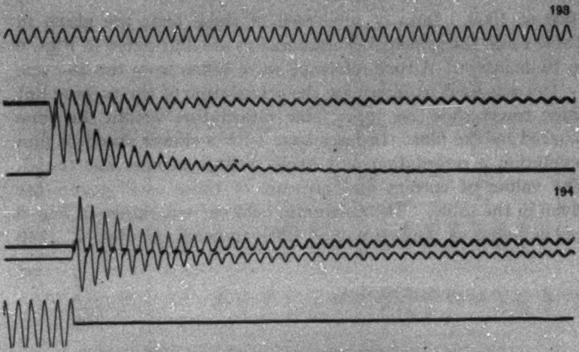
1000 to 4000. Data of seventeen of these tests are given in Table I and the principal characteristics are illustrated in Figs. 6 to 10 inclusive. A time reference wave taken from the 25-cycle system was used to determine the retardation of the turbine but these traces show no appreciable retardation within the time covered by the film. In later tests with a slower speed of film revolution a retardation of ½ cycle in five seconds was found. The values of current and pressure of these oscillograms are given in the table. The maximum field current shown in Fig. 6 had a value of approximately 1200 amperes; in Fig. 7, 1740 amperes; in Fig. 8, 1850 amperes, in Fig. 9, 2000 amperes and in Fig. 10, 2400 amperes. The various data regarding the condition of the field circuit are omitted for reasons given in preceding paragraph.



Trace No. 1—Time reference wave from 25-cycle system.
2—*C* phase generator current; scale 20,100 amperes per in.
3—Generator field current; scale 3,300 amperes per in.
4—*A* phase generator current; scale 23,700 amperes per in.
5—*B* phase generator current; scale 28,200 amperes per in.
6—*A B* generator delta pressure; scale 33,000 volts per in.

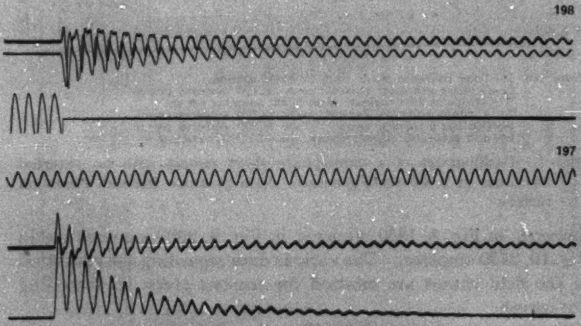
Fig. 7.—Oscillograms of a three-phase short circuit with no external reactance at 3,000 volts generator delta pressure without steam on turbine

In the tests illustrated by Figs. 7 and 9 the unit was first brought above synchronous speed. Steam was then shut off when the speed had dropped to exactly 25 cycles the short-circuiting switch was closed. The oscillograms show that the retardation of the turbine (at the pressures tested) is not affected during the first few seconds of the short circuit by the presence or absence of the steam. In other words, it is



Trace No. 1—Time reference wave from 25-cycle system.
2—*C* phase generator current; scale 42,300 amperes per in.
3—Generator field current; scale 3,300 amperes per in.
4—*A* phase generator current; scale 30,160 amperes per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; 33,000 volts per in.

Fig. 8.—Oscillograms of a three phase short circuit with no external reactance at 4,000 volts generator delta pressure with steam on turbine

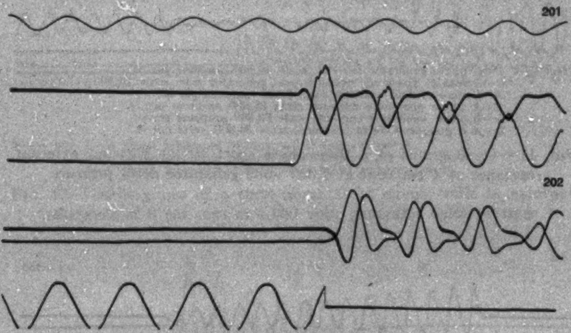


Trace No. 1—Time reference wave from 25-cycle system.
2—*C* phase generator current; scale 42,300 amperes per in.
3—Generator field current; scale 3,300 amperes per in.
4—*A* phase generator current; scale 30,160 amperes per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; 33,000 volts per in.

Fig. 9.—Oscillograms of a three-phase short circuit with no external reactance at 4,000 volts generator delta pressure taken without steam on turbine

entirely a matter of stored energy in the moving mass. In Fig. 8 an interesting trace of field current is shown. The first rush is apparently composed of an alternating current superimposed on the direct current and both were added to the normal excitation current. Both the direct current and alternating current components disappeared simultaneously and at the end of approximately one second the normal value of excitation current was restored. The oscillograms of Fig. 10 were taken to show the wave forms of the generators and the field currents.

From the data obtained from these traces the maximum current at 3000 volts was shown to be 9800 amperes and at 4000 volts 13,000 amperes. Assuming that this proportionality to voltage holds up to normal pressure then the maximum current at normal voltage will be approximately 29,000 amperes or 27 times full load current.

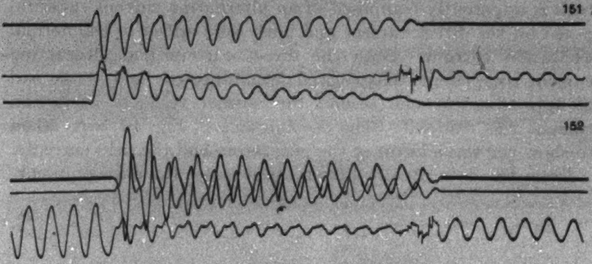


Trace No. 1—Time reference wave from 25-cycle system.
2—*C* phase generator current; scale 42,300 amperes per in.
3—Generator field current; scale 3,300 amperes per in.
4—*A* phase generator current; scale 30,160 amperes per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; scale 33,000 volts per in.

FIG. 10.—Oscillograms of a three-phase short circuit with no external reactance at 4.000 volts generator delta pressure with steam

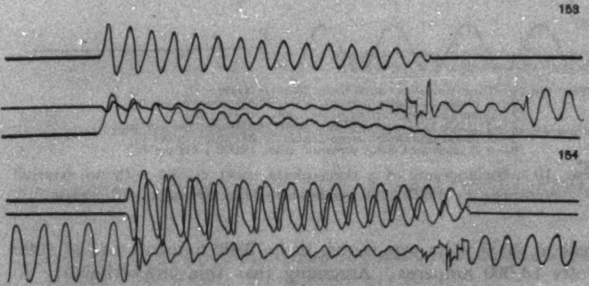
2. THE INSTANTANEOUS SHORT CIRCUIT CURRENT WITH AN EXTERNAL REACTANCE OF 4 PER CENT

It was suggested that perhaps 6 per cent is too high a value for the external reactances and for the purpose of determining the



Trace No. 1—*C* phase generator current; scale 42,300 amperes per in.
2—Across *A* phase oil switch break, generator side; scale 16,500 volts per in.
3—Generator field current; scale 8,400 amperes per in.
4—*A* phase generator current; scale 28,680 amperes per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

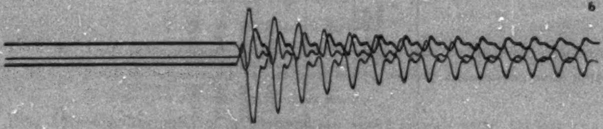
FIG. 11.—Oscillograms of a three-phase short circuit with an external reactance of 4 per cent at 7,000 volts generator delta pressure



Trace No. 1—*C* phase generator current; scale 42,300 amperes per in.
2—Across *A* phase oil switch break, generator side; scale 16,500 volts per in.
3—Generator field current; scale 8,400 amperes per in.
4—*A* phase generator current; scale 28,680 amperes per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

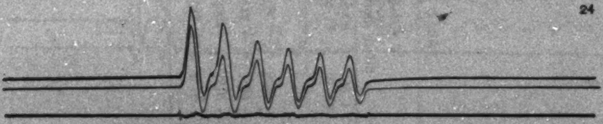
FIG. 12.—Oscillograms of a three-phase short circuit with an external reactance of 4 per cent at 8,000 volts generator delta pressure

effect of the lesser amount a series of tests was made with an external reactance of 4 per cent, using for this purpose part of the turns of the 6 per cent coils. By measurement the section used had a reactance of 0.27 ohms at 25 cycles, thus absorbing 208 volts with a flow of full load current. The data of four of these tests are given in Table II and in the curves of Figs. 11 and 12. Aside from some peculiar pressure conditions at the oil switch no points of particular importance are brought out by the oscillograms. Tests were not made at a pressure higher than 8000 volts with this reactance as the current rushes at that pressure were so high that it was thought inadvisable to subject to the generator or the switches to a greater strain. The current values obtained indicate that at 9000 volts the maximum current would be approximately 18,000 amperes, or 16½ times full load current.



Trace No. 1—*A* phase generator current; 4,680 amperes per in.
2—*B* phase generator current; 3,600 amperes per in.
3—*C* phase generator current; scale 2,210 amperes per in.

Fig. 13.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 1,060 volts generator delta pressure



Trace No. 1—*A* phase generator current from special current transformer; scale 7,920 amperes per in.
2—*A* phase generator current from regular current transformer; scale 8,640 amperes per in.
3—Defective potential transformer fuse.

Fig. 14.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 3,000 volts generator delta pressure

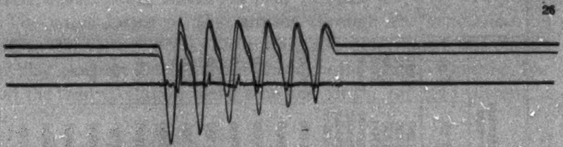
3. THE INSTANTANEOUS SHORT CIRCUIT CURRENT WITH AN EXTERNAL REACTANCE OF 6 PER CENT

There were 146 short circuits made through the 6 per cent reactances. A number of these tests, in addition to determining

TABLE II

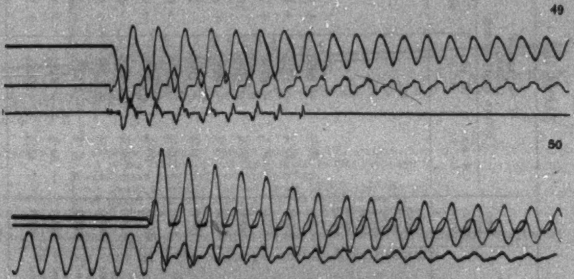
Test No.	Oscillograms	Per cent external reactance	Oil switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	B ph. to ±	C ph. to ±	A ph.	B ph.	C ph.	
59	149 150	4	H-3	3 φ	5000	+ 83%	— 6%	— 89%	7200	10200	7800	
60	151 152	4	"	"	7000	+ 58%	— 41%	— 99%	12000	14700	9900	See Fig. 11
61	153 154	4	"	"	8000	— 51%	—100%	+ 48%	13400	10400	9900	See Fig. 12
62	155 156	.4	"	"	8000	+ 97%	+ 28%	— 69%	10500	14100	14850	

the characteristics and behavior of the reactances, were made for the purpose of experimentation on the oil switches and a few on potential transformer fuses. From the oscillograms obtained, the characteristics of the reactances were studied. In Table III are given the data of twenty-one of these tests and the principal characteristics are illustrated in Fig. 13 to 20 inclusive. A very interesting fact is brought out in these oscillograms. The maximum pressure across the reactance coils is shown to occur in the latter half of the first cycle, indicating that the rate of change of the current is greater in the latter part of the first cycle than in the initial rush. Figs. 13 to 18 inclusive were



Trace No. 1—*A* phase generator current from special current transformer; scale 7,920 amperes per in.
2—*A* phase generator current from regular current transformer; scale 8,640 amperes per in.
3—Defective potential transformer fuse.

FIG. 15.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 4,000 volts generator delta pressure



Trace No. 1—*C* phase generator current; scale 17,100 amperes per in.
2—*A* phase reactance coil drop; scale 18,690 volts per in.
3—Defective potential transformer fuse.
4—*A* phase generator current; scale 15,600 amperes per in.
5—*B* phase generator current; 18,900 amperes per in.
6—*A B* generator delta pressure; 54,300 volts per in.

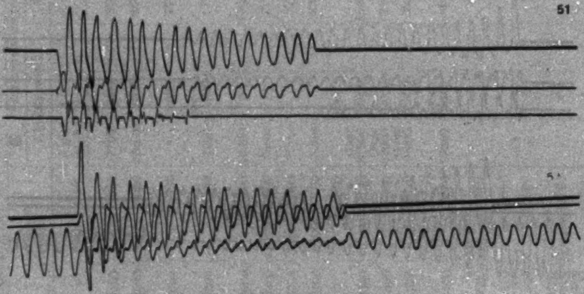
FIG. 16.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 5,500 volts generator delta pressure

TABLE III

Test No.	Oscillo-grams	Per cent ex-ternal react-ance	Oil switch	Kind of short cir-cuit	Gen. delta pres-sure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	B ph. to ±	C ph. to ±	A ph.	B ph.	C ph.	
1	6	6	H-6	3 φ	1050				860	1250	960	See Fig. 13
2	7	6	"	"	1080				1200	1100	770	
3	8	6	"	"	1470				1000	1300	1150	
4	9	6	"	"	1780				1750	1700	2350	
7	21	6	"	"	2000				1950	Regular	transf.	
8	23	6	"	"	2500				3550	Regular	"	
9	24	6	"	"	3000				3600	Regular	"	See Fig. 14
11	26	6	"	"	4000				5300	Regular	"	See Fig. 15
14	45 46	6	"	"	4500	+ 56%	+ 99%	+ 43%	5700	4400	6560	
15	48	6	"	"	5000	+ 21%	— 74%	+ 95%	6800	6800		
16	49 50	6	"	"	5500	— 26%	— 97%	+ 72%	7650	5900	6600	See Fig. 16
17	51 52	6	"	"	6000	+ 50%	— 50%	100%	8300	8800	5100	See Fig. 17
18	53 54	6	"	"	6500	— 12%	— 92%	+ 80%	9100	7560	7400	
19	55 56	6	"	"	7000	+ 94%	+ 19%	— 75%	8200	11300	9700	
20	57 58	6	"	"	7500	+ 55%	— 45%	— 99%	12400	12200		
21	59 60	6	"	"	8000	— 99%	+ 53%	— 47%	7850	13400	14200	See Fig. 18
22	61 62	6	"	"	8500	+ 99%	+ 42%	— 57%	8500	14700	13500	
41	107 108	6	H-3	3 phase grounded	6000	+ 2%	+ 2%	— 86%	7200	9800	8900	
45	117 118	6	"	B phase to ground	9000	+ 47%	— 52%	+100%		15800		See Fig. 19
46	119 120	6	"	B phase to ground	9000	— 63%	+ 98%	+ 35%		8800		
47	121 122	6	"	B phase to ground	9000	— 43%	+100%	+ 57%		9300		See Fig. 20

obtained with three phase short circuits while Figs. 19 and 20 show single-phase short circuits to ground. These latter show the double-frequency field current due to single-phase short circuits and also the pressure rise on the opposite phases. The maximum value of the current obtained during the short circuits with the 6 per cent reactance and at 9000 volts was 15,800 amperes, which is 14½ times full load current.

The wave forms of the current through the reactances as well as the voltage across them were also determined, the circuit for this purpose being closed through the short circuiting bar and the field excitation being adjusted for the full load current of the turbo-generator. The traces obtained under these conditions are shown in Fig. 21. The measured voltage across each coil with this full load current is 328 volts, or a drop of 6.3 per cent.

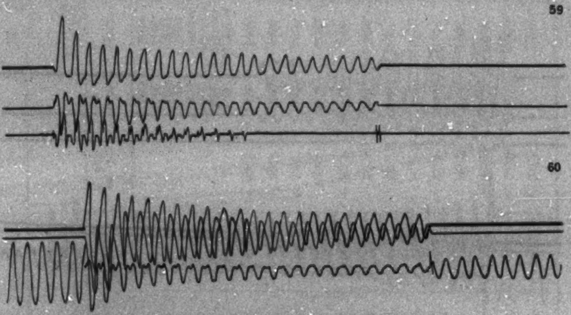


Trace No. 1—*C* phase generator current; scale 17,100 amperes per in.
2—*A* phase reactance coil drop; scale 18,690 volts per in.
3—Defective potential transformer fuse.
4—*A* phase generator current; scale 15,600 amperes per in.
5—*B* phase generator current; 18,900 amperes per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

FIG. 17.—Oscillograms of a three-phase short with an external reactance of 6 per cent at 6,000 volts generator delta pressure

In order to determine whether the amount of steam entering the turbine at the time of a short circuit had any effect on the results, these tests were further extended by including a series in which a load was placed on the turbo-generator and while carrying the same the short circuit was applied. Apparently the results of short circuiting a generator with load are no different from those in which the turbo-generator has no load.

Considerable discussion has been heard in regard to the probable rises in voltage due to non-simultaneous opening of the three phases of the oil switch. In eighteen of the tests made with 6 per cent reactance coils, such non-simultaneous opening is clearly indicated. The voltage rises at the switch are shown in Table III*b*, while Figs. 22 to 27, inclusive, show some of the characteristics under these conditions. Figs. 24 and 25 indicate that some of the contacts of the switch had become badly pitted which was, of course, to be expected after the very severe and continued service during the short circuits. A maximum voltage rise of over 200 per cent at some of the switch breaks is indicated in the oscillograms.



Trace No. 1—*B* phase generator current; scale 40,500 amperes per in.
2—*A* phase reactance coil drop; scale 26,100 volts per in.
3—Defective potential transformer fuse.
4—*A* phase generator current; scale 23,520 amperes per in.
5—*B* phase generator current; scale 27,120 amperes per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

FIG. 18.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 8,000 volts generator delta pressure

Single Phase Short Circuits with 6 *per cent Reactance.* The maximum current on a single phase to ground short circuit was 15,800 amperes, on a short circuit between two phases 12,900 amperes, and on the single phase to ground short circuit with neutral rheostat of 2.5 ohms, 2,580 amperes. Most of the single phase short circuits were made with the generator carrying substation load and pressures were taken across the load bus. Table VI shows the pressure rise on the generator and load bus. It shows that the maximum pressure rise without neutral rheo-

TABLE IIIB

Test No.	Oscillograms	Per cent external reactance	Oil switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Pressures at oil switch						Remarks
												Closing switch			Opening switch			
						A ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph.	*B* ph.	*C* ph.	*A* ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph. to ±	*B* ph. to ±	*C* ph. to ±	
159	269 270	6	K-12	3 φ	5000	—98%	+66%	—32%	9400		9350	7700	7200	*	6600	8800	7600	*C* phase to sw. closed ½ cy before *B* phase closed.
160	271 272	6	"	"	7000	+76%	—18%	—93%	8930		11050	12600	9600	*	5000	9600	*	ditto.
163	275 276	6	"	"	8000	+22%	—73%	+95%	13600		9020	*	9600	*	7700	9600	11200	*B* phase of sw. closed 10% later than *C* phase. See Fig. 22.
164	277 278	6	"	"	8000	—32%	—98%	+63%	12200		9360	4400	11200		?	9600	*	*C* phase of sw. closed before *B* phase and *A* phase.
165	285 286	6	"	"	8000	—95%	+67%	—32%	8460		12400	10500	*	*	17000	12000	?	*B* phase of sw closed about 10% after *C* phase
42	109 110	6	H-3	"	8000	—98%	+65%	—33%	10200	11900	11000	None			2700	gen.	side	*A* phase of sw. closed 10% before *C* phase current.
43	111 112	6	"	"	9000	+89%	+ 6%	—83%	10200	15800	12500	None			2700	gen.	side	ditto. See Fig. 23.
44	113 114	6	"	"	9000	—35%	—98%	+62%	12400	9400	7100	None			2200	gen.	side	ditto
166	279	6	K-12	"	9000						14950		12800	*		20800	17700	ditto
167	281 282	6	"	"	9000	+81%	—11%	—92%	10340		12750	Over 22000	12800	*	13200	21100	16800	ditto. See Fig. 24.
168	283 284	6	"	"	9000	—86%	+86%	0	7800		11900	Over 22000	12000	*	7100	14400	?	ditto. See Fig. 25.
170	287 288	6	"	"	9000	—98%	+67%	—32%	11270		12750	Over 19000	12300	*	None	15200	*	*B* phase of sw. closed ½ cy. after *C* phase and *A* phase.
171	289 290	6	"	"	9000	+40%	—58%	+99%	16170		15300	17600	12800	*	8300	12000	*	*B* phase of switch closed 1 cy. after *C* phase. See Fig. 26.
172	291 292	6	H-3	"	9000	—60%	+99%	+39%	12880		14800							
173	293 294	6	"	"	9000	+70%	—27%	—97%	12220		10540							
202	337 338	6	K-12-8	"	9000	100%	+50%	—50%	7700 7950		12900		*	*		10400	None above normal	*C* phase of sw. closed 10% early. See Fig. 27.
203	339 340	6	" "	" "	9000	+95%	+23%	—72%	9400 9900		11700		*	*		15200	16800	ditto
204	341 342	6	"	"	9000	—70%	+97%	+27%	13450 13400		15800		*	*		None above normal	11200	ditto

*Pressure not above normal.

TABLE IIIA

Test No.	Oscillo-grams	Per cent external reactance	Oil switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	B ph. to ±	C ph. to ±	A ph.	B ph.	C ph.	
24	{69 70	6	H-6	3 ϕ with load	9000	— 15%	— 93%	+ 78%	14100	12200	10800	Water rheostat load of 2000 kw.
26	{71 72	6	"	"	9000	+ 70%	+ 97%	+ 27%	12000	9300	14600	Water rheostat load of 6000 kw.
27	{73 74	6	"	"	9000	— 72	+ 96%	+ 24%	11600	9000	14200	ditto 7440 kw.
28	{75 76	6	"	"	9000	— 63%	+ 98%	+ 36%	11500	8000	12800	ditto 7880 kw.
29	{77 78	6	"	"	9000	— 87%	+ 87%	0%	10000	12000	14200	ditto 7880 kw.

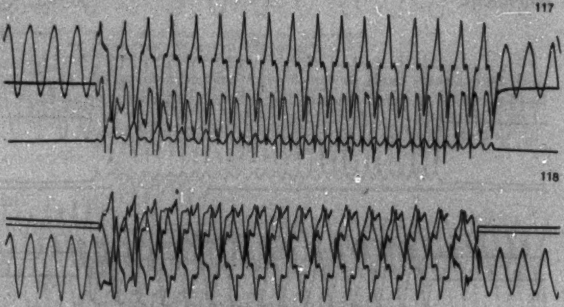
TABLE IV

Test No.	Oscillo-grams	Per cent external reactance	Oil switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	B ph. to ±	C ph. to ±	A ph.	B ph.	C ph.	
63	{157 158	6	H-3	3 phase	9000	+ 92%	+ 12%	— 80%	10500		12450	Taken to show retardation of turbine. See Fig. 28.
64	{159 160	6	"	"	9000	— 87%	+ 87%	0%	10500		13000	ditto
65	161	6	"	"	9000						8770	Wave forms.
66	164	6	"	"	9000	0%	— 87%	+ 87%	12600	12400		ditto
67	{165 166	"	"	"	9000				8200	5650	11700	ditto.

stat is 85 per cent and with neutral rheostat 125 per cent. This shows that while the neutral rheostat greatly lowers the current there is at the same time a greater pressure rise.

4. DURATION OF THE TRANSIENT PHENOMENA INCIDENT TO THE SHORT CIRCUIT UNDER CONDITIONS 1, 2 AND 3

A number of tests were made in which the oil switch was kept closed for several seconds to determine the duration of the transient phenomena. In Fig. 28 are shown the traces of various currents and pressures, and a time wave taken from the 25-cycle system is added for reference. The retardation of the turbine, as previously mentioned, is shown to be approximately ¼ of a cycle in five seconds and the current reaches a constant value in about two seconds. The difference in the rate of decrease of amplitude of the first four cycles of trace No. 1 as compared to this decrease in amplitude of subsequent cycles shows clearly the effect of the field and the armature transients.

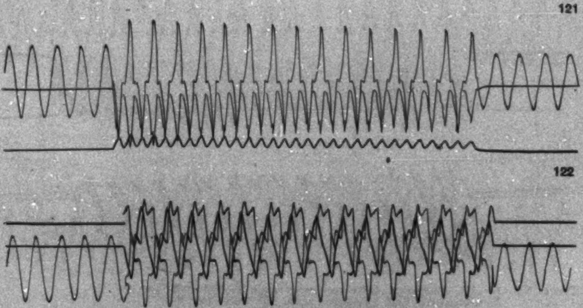


Trace No. 1—*A C* generator delta pressure; scale 52,800 volts per in.
2—Generator field pressure; scale 261 volts per in.
3—Generator field current; scale 8,400 amperes per in.
4—Drop across *B* phase reactance coil; scale 21,300 volts per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

FIG. 19.—Oscillograms of a *B* to ground short circuit with an external reactance of 6 per cent at 9,000 volts generator delta pressure

5. THE EFFECT ON THE GENERATOR OF THESE SHORT CIRCUIT CURRENTS

A careful examination was made of the generator after each series of tests but no effect whatever could be detected. At the instant of short circuit in many cases a flash was seen within the generator. This was caused by the volatilized parts of the carbon brushes at the collector rings of the field circuit, and also by the induction of very large eddy currents in the field core. Trace No. 3 in Fig. 28 shows the variation in field current during the short circuit. This current may rise as high as 3,500 amperes due to induction from the armature circuit. The normal excitation at full load and unity power factor is 400 amperes. It is apparent from the above that the insertion of the 6 per cent coils renders the turbo-generator practically immune against failure due to the stresses incident to short circuits beyond the reactances.



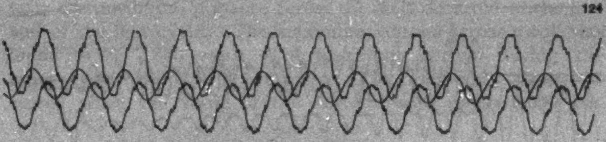
Trace No. 1—*A C* generator delta pressure; scale 54,300 volts per in.
2—Generator field pressure; scale 432 volts per in.
3—Generator field current; scale 8,400 amperes per in.
4—Drop across *B* phase reactance coil; scale 21,300 volts per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; 54,300 volts per in.

FIG. 20.—Oscillograms of a *B* to ground short circuit with an external reactance of 6 per cent at 9,000 volts generator delta pressure

6. THE BEHAVIOR OF THE REACTANCE COILS

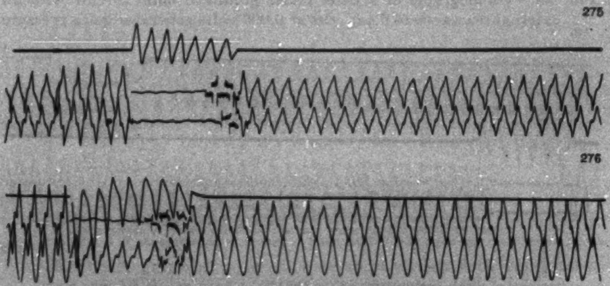
Early in the tests large iron nails were placed on the floor near the reactances to indicate the strength of the field at the time of short circuit. In test No. 23 one of these nails about two feet distant from the lower turn was drawn into the B phase coil.

A full load run was made to determine the heating of the coils and pieces of brass bar, copper and iron were placed near them. The generator was short circuited through the coils and with a current of 770 amperes a constant temperature was reached at the end of five hours. During this run the oscillogram of Fig. 21 was obtained. The tests showed that there is practically no heating in brass or copper placed near the coils. Iron bars 1 by $\frac{3}{4}$ in. in section forming a framework of an iron screen showed a temperature rise of 24 deg. cent. when placed within 12 in. of the coils.



Trace No. 1—Drop across *A* phase reactance coil, 328 volts.
2—*A* phase generator current, 768 amperes.
3—*A B* generator delta pressure, 576 volts.

Fig. 21.—Oscillograms showing wave forms of short circuit with full load current through external 6 per cent reactance on a three-phase short

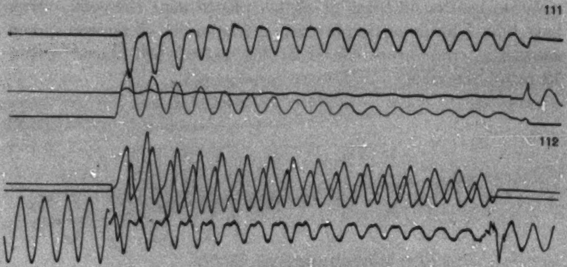


Trace No. 1—*C* phase generator current; scale 51,000 amperes per in.
2—Across *B* phase oil switch break; scale 48,000 volts per in.
3—Across *C* phase oil switch break; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—Across *A* phase oil switch break; scale 33,000 volts per in.
6—*A B* generator delta pressure; scale 54,000 volts per in.

Fig. 22.—Oscillograms showing three-phase short circuit with an external reactance of 6 per cent at 8,000 volts generator delta pressure

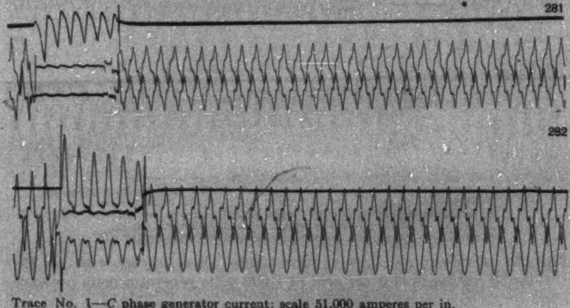
Various devices were applied to record possible movement of the coils but no such movement was detected. In the latter part of the tests the heavy braces at the top were disconnected but even with this support removed the coils showed no tendency to move.

The magnetic pull due to the field was tested by holding a



Trace No. 1—*C* phase generator current; scale 52,300 amperes per in.
2—Across *A* phase oil switch break, generator side; scale 31,500 volts per in.
3—Generator field current; scale 8,400 amperes per in.
4—*A* phase generator current; scale 28,680 amperes per in.
5—*B* phase generator current; scale 33,900 amperes per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

Fig. 23.—Oscillograms of a three-phase grounded short circuit with an external reactance of 6 per cent at 9,000 volts generator delta pressure



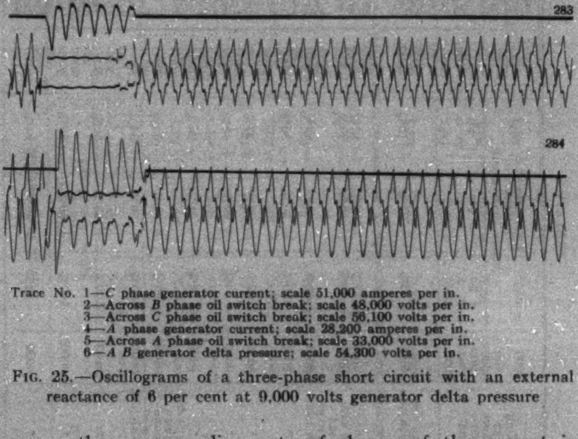
Trace No. 1—*C* phase generator current; scale 51,000 amperes per in.
2—Across *B* phase oil switch break; scale 48,000 volts per in.
3—Across *C* phase oil switch break; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—Across *A* phase oil switch break; scale 33,000 volts per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

Fig. 24.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 9,000 volts generator delta pressure

sheet of iron screen 30 in. from one of the coils at time of short circuit. The screen was arranged to stay in position by means of a light string held by an observer, but not the slightest pull could be detected.

No pressure rises across the end turns of the coils were found. As already mentioned in the first paragraph of series No. 3, tests the maximum pressure across the coils occurred in the last half of the first cycle. The maximum voltage across a coil was found to be 7,850 volts. The maximum current during the same cycle was 11,700 amperes. The maximum drop occurred when the value of the current was about 9,000 amperes; the corresponding rate of change of the current is

$$\frac{d\,i}{d\,t} = \frac{e - i\,R}{L} = \frac{7850 - 670}{0.0027} = 2{,}660{,}000 \text{ amperes per second.}$$



Trace No. 1—*C* phase generator current; scale 51,000 amperes per in.
2—Across *B* phase oil switch break; scale 48,000 volts per in.
3—Across *C* phase oil switch break; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—Across *A* phase oil switch break; scale 33,000 volts per in.
6—*A B* generator delta pressure; scale 54,300 volts per in.

FIG. 25.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 9,000 volts generator delta pressure

7. THE EFFECT OF THE INSTALLATION OF REACTANCE COILS ON THE STABILITY OF THE SYSTEM

The stability of the system during cable breakdowns depends primarily on two things; first, steadiness of voltage, and second, steadiness of speed. The use of the reactances reduces the torque on the generators to such a point that the speed is not materially affected even by short circuits on the bus. This is

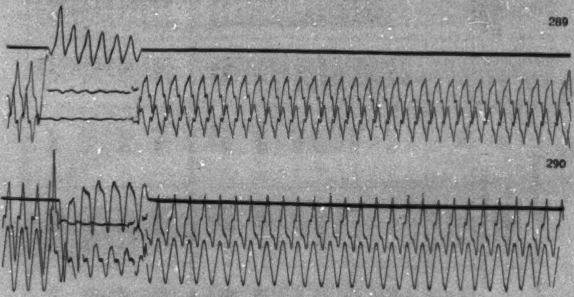
TABLE V

Test No.	Oscillo-grams	Per cent external reactance	Oil switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph.	*B* ph.	*C* ph.	
49	125 126	6	H-3	3 φ with load	9000	— 93%	+ 77%	— 18%	3850 11000	Substation Generator		Generator carrying 5 substa. load of 1340 kw. not connected to system. See Fig. 29.
50	127 128	6	"	"	9000	+ 87%	0%	— 87%	3500 11000	Substation Generator		Gen. carrying 5 substa. load of 770 kw. not connected.
51	132	6	"	*A B* with load	9000	+ 59%	— 49%	— 99%	12900	Generator		Gen. carrying 5 substa. load of 650 kw. not connected.
52	129 130	6	"	*A* φ to gr. with load	9000	+ 58%	— 41%	— 99%	2550 14800	Substation Generator		ditto.
97	229 230	6	"	"	9000	100%	+ 50%	— 50%	8180 8000 220	Total Generator Substation		Generator carrying Market St. rotary running idle.
98	232	6	"	"	9000	— 62%	+ 98%	+ 37%	13100 360	Generator Substation		ditto. See Fig. 30.
99	233 234	6	"	"	9000	— 55%	+ 99%	+ 45%	13600 12200 360	Total Generator Substation		ditto. See Fig. 31.
100	235 236	6	"	"	9000	+ 72%	— 24%	— 96%	11900 11900 530	Total Generator Substation		Generator carrying Market St. rotary connected to D. C. system. See Fig. 32.
102	237 238	6	"	*A* φ to ground	9000	+ 98%	+ 34%	— 63%	9000			
103	239 240	6	"	*A* φ to grd. with load	9000	100%	+ 50%	— 50%	9000 8260 550	Total Generator Substation		Generator carrying split-pole rotary running idle.
104	241 242	6	"	"	9000	100%	+ 50%	— 50%	9000 8000 560	Total Generator Substation		ditto. See Fig. 33.
105	243 244	6	"	"	9000	100%	+ 50%	— 50%	9000 8740 560	Total Generator Substation		Generator carrying split-pole rotary connected to d. c. system. See Fig. 34.
106	245 246	6	"	"	9000	— 72%	+ 96%	+ 24%	14400 12700 1130	Total Generator Substation		Generator carrying 2000 kw. frequency changer. See Fig. 35.

TABLE V. (*Continued.*)

Test No.	Oscillograms	Per cent external reactance	Ol switch	Kind of short circuit	Gen. delta pressure	Y voltages at instant before short circuit			Maximum currents			Remarks
						A ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph.	*B* ph.	*C* ph.	
107	247 248	6	*H*-3	*A* φ to grd. with load	9000	100%	+ 50%	— 50%	9360 8000 1020	Total Generator Substation		ditto.
151	259 260	6	"	"	9000	+ 90%	+ 8%	— 82%	10500 9400 470	Total Generator Substation		Generator carrying Market St. rotary connected to d.c. system.
155	261 262	6	"	"	9000	+ 98%	+ 34%	— 72%	8500 8920	Total Generator		ditto.
156	263 264	6	"	"	9000	100%	+ 50%	+ 50%	10500 10300 380	Total Generator Substation		ditto. See Fig. 36.
157	265 266	6	"	"	9000	+ 90%	+ 8%	— 63%	10700 10500 330	Total Generator Substation		ditto. See Fig. 37.
158	267 268	6	"	"	9000	+ 98%	+ 34%	— 64%	8500 8460 340	Total Generator Substation		ditto.
In the four following tests a 2½ ohm resistance was inserted to the neutral connection to ground												
197	327 328	6	"	*A* φ to grd. with load	9000	+ 65%	— 33%	— 98%	2550 2350 150	Total Generator Substation		Generator carrying standard rotary connected to d. c. system.
198	329 330	6	"	"	9000	100%	+ 50%	— 50%	2550 2350 150	Total Generator Substation		ditto. See Fig. 38.
199	331 332	6	"	"	9000	+ 92%	+ 12%	— 80%	2450 2280 130	Total Generator Substation		Generator carrying standard rotary connected to d.c. system. See Fig. 39.
200	333 334	6	"	"	9000	+ 92%	+ 12%	— 80%	2580 2280 140	Total Generator Substation		ditto.

shown clearly by the small retardation of the generator, shown in Fig. 28 previously referred to. The voltage on the bus, however, is directly dependent on the resistance of the short circuit from the bus to the fault and back, as well as on the nature of the fault, and is, therefore, practically independent of the reactances. If then the voltage drops to such a point that the synchronous apparatus connected to the system feeds back sufficient energy to actuate the overload relays on the substation units, the oil switches on these units will be opened, *i.e.*, the load will drop off. If the bus voltage does not reach a very low point or if the overload relays in the substation are provided with fixed time elements which will make them inoperative, short of, say one second, then the reactance in the generator circuit will by the phase displacement of the current cause the synchronizing component of the current to be greater, thereby making the system more stable. This is illustrated in Fig. 40 where $O\,A$ represents the generator e.m.f., $O\,B$ the counter e.m.f. of the substation unit, and $O\,C$ the resultant e.m.f. causing a cross current to flow. This cross current with only a small amount of reactance in the circuit has the direction $O\,I_1$, lagging behind $O\,C$ by angle α. This angle is increased to α', the current vector then being $O\,I_2$, when the reactance in the circuit is in-

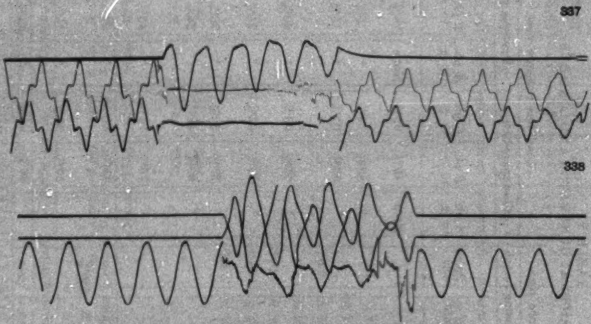


Trace No. 1—*C* phase generator current; scale 51,000 amperes per in.
2—Across *B* phase oil switch break; scale 48,000 volts per in.
3—Across *C* phase oil switch break; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—Across *A* phase oil switch break; 33,000 volts per in.
6—*A* phase to neutral generator pressure; scale 32,700 volts per in.

FIG. 26.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 9,000 volts generator delta pressure

creased as by the installation of generator reactances; the greater the reactance, the greater will the angle α be. The component of I in phase with the negative vector of $O\,B$, or $O\,B'$, is the energy or synchronizing current, and the increase in this value from $O\,I_2$ to $O\,I_4$ due to increase of angle α is clearly seen. All angles and the current vectors are purposely very much exaggerated for sake of clearness.

Another advantage gained by having the reactances in the armature leads lies in the fact that with lowering of the bus pressure, as by a short circuit, the generator voltage is not reduced by the same amount due to the drop in the reactances themselves. Normal pressure is thus restored more quickly.



Trace No. 1—*C* phase generator current, scale 35,100 amperes per in.
2—Across *B* phase oil switch break; scale 48,000 volts per in.
3—Across *C* phase oil switch break, scale 56,100 volts per in.
4—*A* phase generator current; regular transformer, scale 28,200 amperes per in.
5—*A* phase generator current from special current transformer, scale 29,100 amperes per in.
6—*A* phase to neutral generator pressure, scale 32,700 volts per in.

FIG. 27.—Oscillograms of a three-phase short circuit with 6 per cent reactance at 9,000 volts generator delta pressure

Various substation units of the operating system were connected to the turbo-generator under test and short circuits were then produced to note the behavior of these substation units.

It was, of course, impossible to exactly reproduce conditions of faults in the system therefore a definite comparison of the action with and without reactances cannot be made. However, from the test results the stability of the various types of substation units can be determined. The desirability of some minor changes in substation relay settings is also indicated.

TABLE VI
PRESSURE RISES AT GENERATOR AND LOAD BUS

Test No.	Oscillograms	Per cent reactance	Kind of short circuit	Gen. delta pressure before short circuit	Generator pressure rises				Load bus pressure rises						Remarks
					Closing switch		Opening switch		Closing switch			Opening switch			
					Phase	Per cent	Phase	Per cent	*A* ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph. to ±	*B* ph. to ±	*C* ph. to ±	
97	229	6	*A* φ to gr. with load	9000					None	46%	62%	None	18%	13%	Generator carrying Market St. rotary running idle.
99	233	6	"	9000					"	83%	72%	"	5%	85%	ditto
100	235	6	"	9000					"	53%	61%	"	15%	7%	Generator carrying Market St. rotary connected to d.c. system.
102	237	6	*A* φ to ground	9000					"	60%	60%	"	40%	10%	Tests made without sub-station load.
103	239	6	*A* φ to gr. with load	9000					"	57%	63%	"	25%	8%	Generator carrying split pole rotary running idle.
104	241	6	"	9000					"	57%	59%	"	30%	10%	ditto
105	243	6	"	9000					"	60%	42%	"	24%	None	Generator carrying split pole rotary connected to d.c. system.
106	245	6	"	9000					"	75%	74%	"	45%	23%	Generator carrying 2000 kw. frequency changer.
107	247	6	"	9000					"	41%	37%	"	30%	5%	ditto
109	252	6	3 phase	9000	*A B*	None	*A B*	136%							
151	259	6	*A* φ to gr. with load	9000					"	59%	56%	"	16%	?	Generator carrying Market St. rotary connected to d.c. system
155	261	6	"	9000					"	80%	94%	"	22%	53%	ditto

TABLE VI (*Continued.*)
PRESSURE RISES AT GENERATOR AND LOAD BUS

Test No.	Oscillograms	Per cent reactance	Kind of short circuit	Gen. delta pressure before short circuit	Generator pressure rises				Load bus pressure rises						Remarks
					Closing switch		Opening switch		Closing switch			Opening switch			
					Phase	Per cent	Phase	Per cent	*A* ph. to ±	*B* ph. to ±	*C* ph. to ±	*A* ph. to ±	*B* ph. to ±	*C* ph. to ±	
156	263	6	*A* ϕ to gr. with load	9000					None	74%	83%	None	40%	67%	generator carrying standard rotary connected to d.c. system.
157	265	6	"	"					"	70%	73%	"	36%	62%	ditto
158	267	6	"	"					"	70%	83%	"	36%	48%	ditto
160	272	6	3 phase	7000	*A B*	30%	*A B*	7%							Defective oil switch
161	274	6	"	5000	*A B*	None	*A B*	40%							ditto
164	278	6	"	8000	*A B*	93%	*A B*	None							ditto
167	282	6	"	9000	*A B*	46%	*A B*	"							ditto
168	284	6	"	9000	*A B*	43%	*A B*	25%							ditto
169	286	6	"	8000	*A B*	None	*A B*	?							ditto
170	298	6	"	9000	*A B*	Over 70%	*A B*	None							ditto
184	310	6	*A B* through bomb fuse		*A B*	20%									Pressure rise on fuse test.
172	290	6	3 ϕ	9000	*A B*	62%	*A B*	None							Defective oil switch.
In the following tests a 2½ ohm resistance was inserted in the neutral to ground															
197	327	6	*A* ϕ to gr.	9000					None	104%	20%	None	113%	20%	Generator carrying Market St. rotary connected to d.c. system.
198	329	6	"	"					"	113%	35%	"	113%	35%	ditto
199	331	6	"	"					"	120%	35%	"	120%	35%	ditto
200	333	6	"	"					"	126%	33%	"	126%	33%	ditto

TABLE VII.

Substation	Line			Unit		
	No.	Size	Length	No.	Capacity	Class
Market St..	58	4/0	17900′	3	1000 kw.	Standard converter 275 v. 214 r.p.m.
Indiana St..	87	4/0	24600′	1	1000 kw.	Split pole converter 270 v. 300 r.p.m.
Lake View..	133	250,000 cm.	35900′	4	1000 kw.	25/60 cy. frequency ch.
42nd St....	138	4/0				
	331	250,000 cm.	40500′	5	2000 kw.	Standard converter 600 v.d.c.
	332	250,000 cm.				
Grand Ave..	90	250,000 cm.	42500′	1	2000 kw.	Standard converter 600 v.d.c.

Relay settings

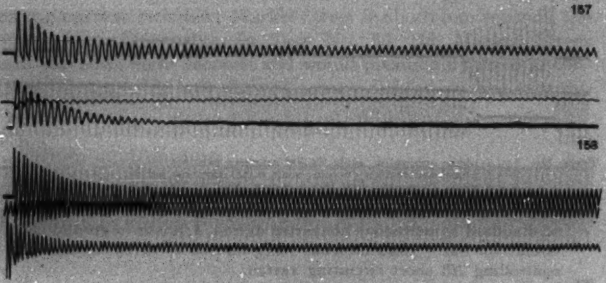
Substation	Unit			Substation line switch			Generating station line switch		
	Amperes			Amperes			Amperes		
	Core	2 sec.	Inst.	Core	4 sec.	Inst.	Core	2 sec.	Inst.
Market St..........	155	233	310		No relays		400	560	750
Indiana St.........	155	233	310		″		400	560	750
Lake View.........	155	233	310		″		480	670	900
		4 sec.							
42nd Ave..........	240	256	640	300	384	766	400	560	750
		2 sec.							
Grand Ave.........	310	465	620			650	480	670	900
Fault.............	(Relay controlling short circuiting switch)								2000

Substation	Line			Unit		
	No.	Size	Length	No.	Capacity	Class
Hyde Park..	144	4/0	32,700 ft.	2	2000 kw.	25/60 F. C. 300 r.p.m. 9000/4000 volts.
Jackson Blvd......	9 130	4/0 4/0	5,500 ft. 14,400 ft.	2	1000 kw.	Standard converter 250 volts, 214 r.p.m.

Substation	Specified relay settings					
	Unit amperes			Generating station Line-switch amps.		
	Core	2 sec.	Inst.	Core	2 sec.	Inst.
Hyde Park.....	310	465	620	400	560	750
Jackson Blvd...	155	233	310	400	560	750

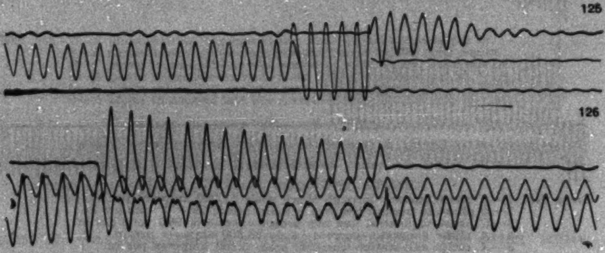
Because of the impossibility of definite and complete conclusion it was thought advisable to give the data of these tests in some detail so that any who may care to do so can study them.

Tests with a Group of Substation Units. In this series of tests five substation units in as many substations were used. The data on the lines, units and relay settings concerned are given in Table VII.



Trace No. 1—*C* phase generator current; scale 42,300 amperes per in.
2—Across *A* phase oil switch break generator side; scale 16,500 volts per in.
3—Generator field current; scale 8,400 amperes per in.
4—*A* phase generator current; scale 28,680 amperes per in.
5—Time reference wave from 25 cycle system.
6—*A B* generator delta pressure; scale 54,300 volts per in.

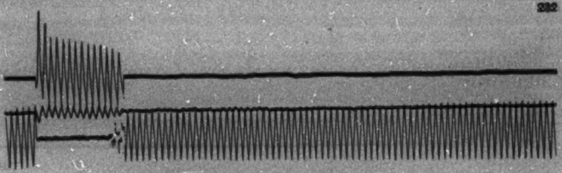
FIG. 28.—Oscillograms of a three-phase short circuit with an external reactance of 6 per cent at 9,000 volts generator pressure to show retardation of turbine.



Trace No. 1—*A* phase substation current; scale 16,980 amperes per in.
2—*A B* line bus pressure, scale 51,900 volts per in.
3—Defective connection.
4—*A* phase generator current; scale 28,680 amperes per in.
5—Time reference wave from 25 cycle system.
6—*A B* generator delta pressure; scale 54,300 volts per in.

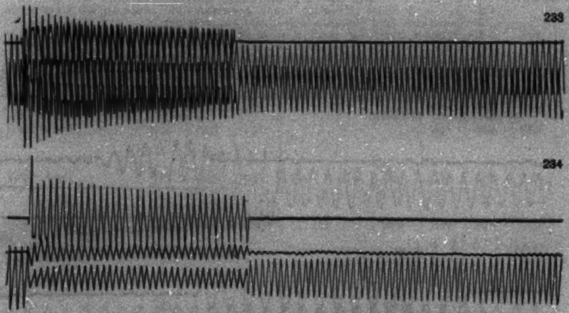
FIG. 29.—Oscillograms showing the effect of 6 per cent reactance coils on the operation of substations during a three-phase short circuit on bus

Under "relay settings" are given the current values for which the apparatus was adjusted at the last periodical check. The primary amperes are shown which are required to raise the



Trace No. 1—*A* phase generator; scale 28,200 amperes per in.
2—*A* phase sub-station current, scale 6,000 amperes per in.
3—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

Fig. 30.—Oscillogram showing effect of reactance coils on the operation of standard synchronous converter during *A* phase to ground short circuit on bus. Instantaneous relay on 400:1 current transformer controlling *H*3 short circuiting switch.



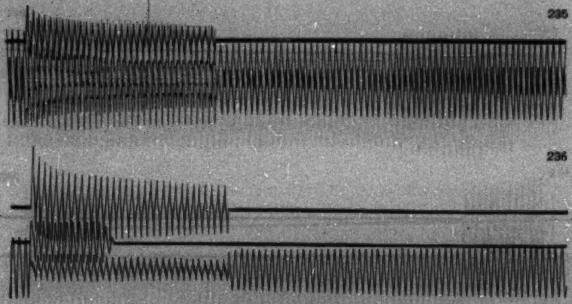
Trace No. 1—*A* phase current through short, scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 29,400 volts per in.
3—*C* phase to neutral line bus pressure; scale 33,900 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase sub-station current; scale 5,160 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

Fig. 31.—Oscillogram showing effect of reactance coils on the operation of standard synchronous converter during *A* phase to ground short circuit on bus. Inverse time element relay on 400:1 current transformer controlling *H*3 short circuiting switch

core without time element attachments and primary amperes with time element attachments to raise the core in two seconds and instantaneously. In all substation tests the same units and relay settings were used unless otherwise mentioned.

In all four tests the five units were connected only to the 25 cycle system and there was, therefore, no possible back feed other than that due to the stored energy in the rotating members. Table V gives the oscillographic data for all the operating tests.

In Test No. 49, Fig. 29, all substation units opened the alternating current switches; Market Street in about four seconds, the others instantaneously. In Test No. 50, the Market Street unit stayed in eight seconds and would presumably have so continued but as the unit showed some sparking on the commutator it was disconnected by the operator. All other units opened the alternating current switches on reverse overload. In Test No. 51 on a single-phase short circuit between *A* and *B* phases, the Market Street unit stayed in, but the others again opened the alternating current unit switches on reverse overload. In Test No. 52 all the units stayed in except Indiana Street and even this unit hung on for about one second.



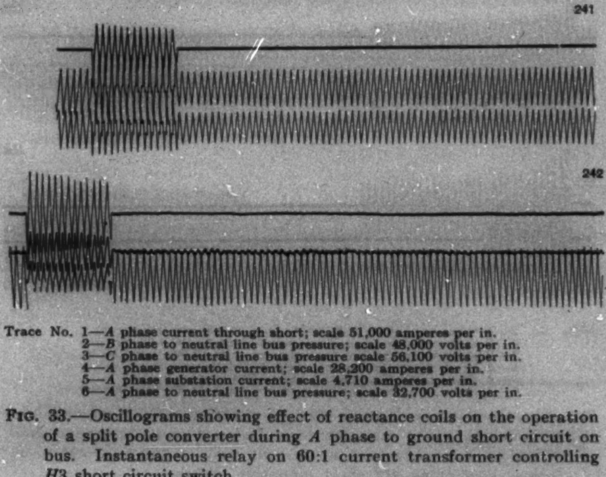
Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 29,400 volts per in.
3—*C* phase to neutral line bus pressure; scale 33,900 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase substation current; scale 3,710 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

Fig. 32.—Oscillograms showing effect of reactance coils on the operation of standard synchronous converter during *A* phase to ground short circuit on bus. Inverse time element relay on 400:1 current transformer controlling *H*3 short circuiting switch.

In none of the tests were the line switches in the generating station opened.

Tests with Single Substation Units of Various Types. This series of tests was started with the idea of checking the operation of the individual units used in Tests No. 49 to 52 inclusive, thus eliminating any effect of cross current between substations.

Standard Converter with Induction Regulator. The first unit to be tried was No. 3 synchronous converter at the Market Street substation and for tests No. 97 and 98, Fig. 30, the H-3 short circuiting switch at Fisk Street was controlled by the same instantaneous relay used in the preceding tests connected to a 400 to 1 current transformer. In both tests the Market Street converter was running idle, connected only to the alternating current end, and in both tests the unit remained connected through to the line bus after the short. For Test No. 99, Fig. 31, and Test No. 100, Fig. 32, a new type of overload relay was substituted for the instantaneous relay as the control for the H-3 short circuit switch, and in Test No. 99 with the Market Street machine connected only to the alternating current end the unit remained in synchronism. In Test No. 100, Fig. 32, however, when the Market Street unit was connected to the direct current bus in parallel with converters No. 2 and 3 and a

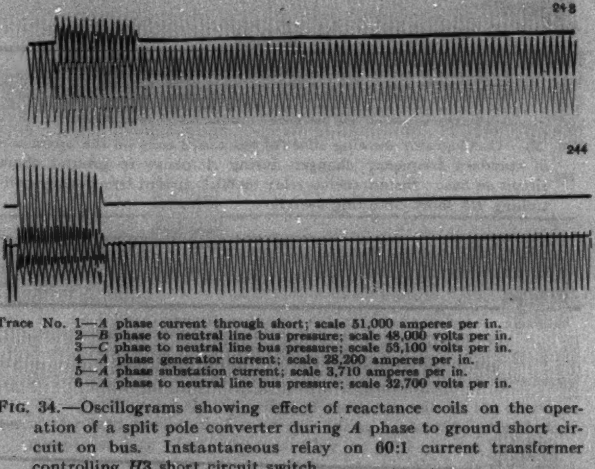


Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase substation current; scale 4,710 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

FIG. 33.—Oscillograms showing effect of reactance coils on the operation of a split pole converter during *A* phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling *H*3 short circuit switch

storage battery, the machine tripped out on both the alternating current and direct current sides. At the instant of short circuit in this last test the battery ammeter showed a current of 10,000 amperes and synchronous converter No. 2 ammeter about 2000 amperes.

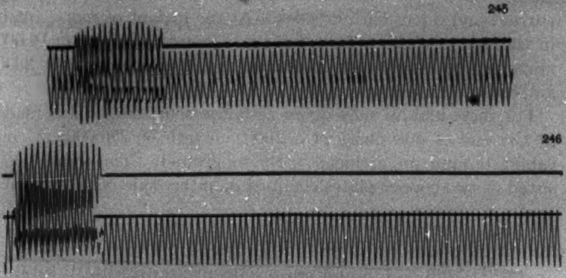
For these and all subsequent tests the short circuit was made at the end of one phase of a 200-ft. length of 250,000-cir. mil cable through an artificial fault to ground. This fault consisted of two copper plates clamped on either side of an asbestos board, through which a small hole was drilled. The two coppers represented the conductor and lead sheath of the cable while the asbestos board replaced the insulation. In this series of four tests a short length of No. 36 *I a I a* wire was connected between plates through the hole in the asbestos to start the short circuit, but in Test No. 102 and the remaining trials of substation operation the fuse wire was omitted as it was found that the artificial fault broke down gradually without previous fusing, thus more nearly duplicating actual fault conditions.



Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure; scale 53,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase substation current; scale 3,710 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

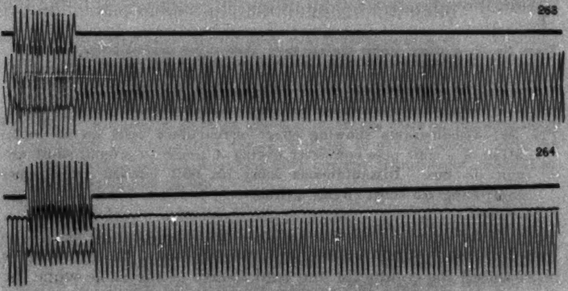
FIG. 34.—Oscillograms showing effect of reactance coils on the operation of a split pole converter during *A* phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling *H*3 short circuit switch.

Test No. 151 is a repetition of test No. 100 using the in-



Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase substation current; scale 3,710 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

FIG. 35.—Oscillograms showing effect of reactance coils on the operation of standard frequency changer during *A* phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling *H*3 short circuiting switch

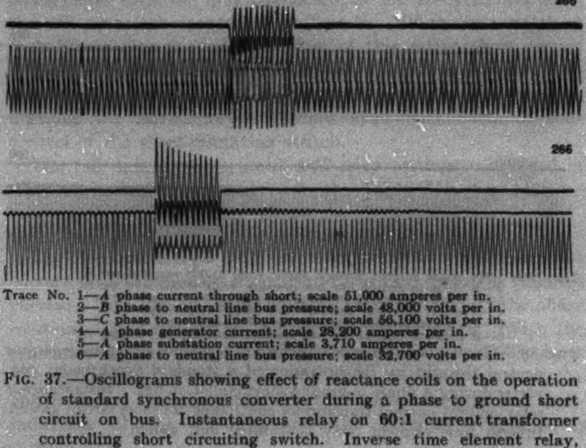


Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase substation current; scale 3,710 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

FIG. 36.—Oscillograms showing effect of reactance coils on the operation of standard synchronous converter during *A* phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling short circuit switch. Inverse time element relay controlling unit switch

stantaneous relay connected to a 60 to 1 current transformer to control the H-3 short-circuiting switch, as it was hoped that under these conditions the unit might remain connected. At the instant of short, however, the direct current circuit breakers opened on reverse current and all three phases of the unit overload relays tripped out the oil switches.

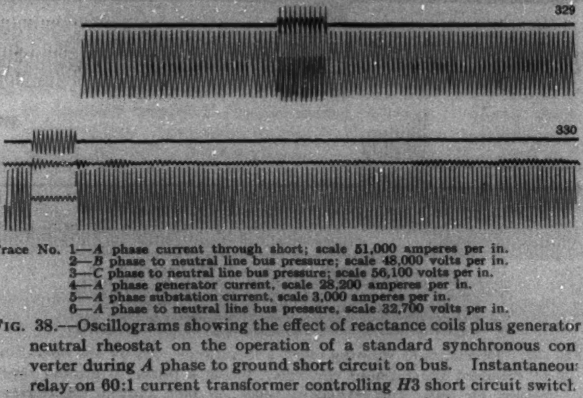
Tests No. 155, 156, 157 and 158 were made with a new type of inverse current relay previously used in certain of the former tests for control of the alternating current short-circuiting switch. This relay was installed at Market Street in place of the standard relay equipment to control the alternating current unit switch. In Tests No. 155 and 156, Fig. 36, and Test No. 158 the direct current circuit breakers opened on reverse current before the relay cones raised sufficiently to trip out the oil switch and in Test No. 157, Fig. 37, the unit remained connected to both the direct current and alternating current systems.



Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure; scale 56,100 volts per in.
4—*A* phase generator current; scale 28,200 amperes per in.
5—*A* phase substation current; scale 3,710 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

FIG. 37.—Oscillograms showing effect of reactance coils on the operation of standard synchronous converter during a phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling short circuiting switch. Inverse time element relay, controlling unit switch

In all previous operating tests the neutral of generator No. 10 was connected directly to ground, the single phase short circuit current being limited therefore only by the reactance coils. As no satisfactory operating results could be obtained under these conditions it became evident that the neutral rheostat must be retained as an essential part of the system and the present group of tests were therefore made to determine the operating results when rheostat was included in the connection to short circuit. The unit at the Market Street substation which had previously been used was not available and a similar unit at the Jackson Boulevard substation was therefore used. In Tests No. 197 and 198, Fig. 38, the alternating current switch of this unit was controlled by the new type reverse current relay, while in Tests No. 199, Fig. 39, and Test No. 200 the alternating current switch control was reconnected to the standard relay equipment.



Trace No. 1—*A* phase current through short; scale 51,000 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure; scale 56,100 volts per in.
4—*A* phase generator current, scale 28,200 amperes per in.
5—*A* phase substation current, scale 3,000 amperes per in.
6—*A* phase to neutral line bus pressure, scale 32,700 volts per in.

FIG. 38.—Oscillograms showing the effect of reactance coils plus generator neutral rheostat on the operation of a standard synchronous converter during *A* phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling *H*3 short circuit switch. Inverse time element relay controlling unit switch

In all four tests although the unit was connected to the direct current auxiliary bus and thence through four feeders to the direct current network, the generator neutral rheostat so limited the short circuit current that the rotary remained connected to both the alternating current and direct current systems.

Converter with Regulating Field (*Split Pole*). Tests No. 102, 103, 104 and 105 were made with the generator carrying the Indiana St. 1000-kw. split pole converter. In all tests the short-circuiting switch was controlled by the instantaneous relay, as the split pole converter opened on the alternating current end. In Tests No. 103 and 104, Fig. 33, when running disconnected from the direct current end, and in Test No. 105, Fig. 34, when running on the direct current auxiliary bus connected to the direct current network through three feeders. It was, therefore, not necessary to make further tests with the time element control of the short-circuit switch.

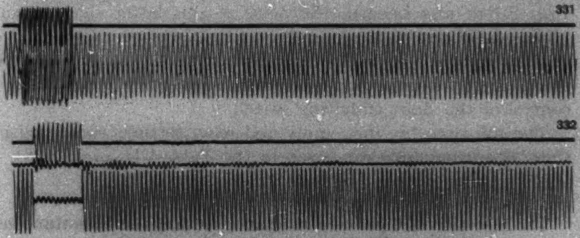
Frequency Changer Unit (9000 *Volt*, 25 *Cycle Synchronous Motor*). Tests No. 106, Fig. 35, and Test No. 107 were made with a standard 2,000-kw. frequency changer at the Hyde Park substation instead of a 1,000-kw. frequency changer at the Lake View substation used in Tests No. 49 to 52 inclusive. In both trials made with the unit connected to the 25-cycle end only, the unit oil switch opened and in Test No. 106 the line switch at Fisk Street also opened, the noise of this latter short circuit giving the observers the impression that it was very severe. No trials were made with the time limit relay as the unit was too unstable for satisfactory operation even with instantaneous control of the short circuiting switch.

The full data on lines, units and relay settings concerned in these operating tests are given in the Table VII, page 1178.

GENERAL DISCUSSION OF RESULTS

The insertion of 6 per cent reactance reduces the instantaneous current on a three phase short from 27 to 14.5 times the full load current. In addition to this, account must be taken of the phase relation of this current to the voltage producing it. With the reactances in, the total resistance of the circuit was 0.033 ohms. The maximum Y pressure is 7350 volts, the impedance of the entire circuit including the effect of armature reaction, self-induction of the winding and the external reactance is $\frac{7350 \text{ volts}}{15{,}800 \text{ amperes}}$ or 0.46 ohms, therefore, the power factor at this current is apparently $\frac{0.033}{0.46}$ or 7.2 per cent. Without external reactance the resistance of the total circuit is that of the armature winding alone, or 0.025 ohms. The impedance of the armature circuit from test equals $\frac{7350 \text{ volts}}{29{,}000 \text{ amperes}}$ or 0.25 ohms per phase therefore, the power factor of the current is apparently 10 per cent. As this armature circuit is embedded in iron there must be a very appreciable hysteresis loss which is true energy. The actual power factors are therefore probably several times the values given above. The decrease in power factor due to the reactances is in greater ratio than 10 to 7.2 (from above values) as the hysteresis component of the energy is also smaller with the lesser current resulting from the insertion of reactances. The energy due to a sudden short circuit is reduced in proportion to the power component of the current, therefore, the shock on the generator will be a great deal less with reactances than without reactances. The strains on the coils, however, are directly proportional to the square of the current and therefore would be over three times as great without external reactance as with such reactance.

If the two machines are thrown together 180 deg. out of phase the e.m.f. in the entire circuit is doubled as are also the resistances and reactances. Therefore the armature current is the same as if the machines were short circuited at their terminals, that is, a possible maximum of 15,800 amperes. If the machines are thrown into a circuit partly out of step the maximum current is equal to the short circuit current multiplied by the sine of half the angle of phase displacement. At Fisk Street five machines are run in parallel during the peak. Where four machines are feeding a bus and the fifth is thrown in 180 deg. out of step the total e.m.f. is doubled while the resistances and reactances are increased only 1.25 per cent. This means that there



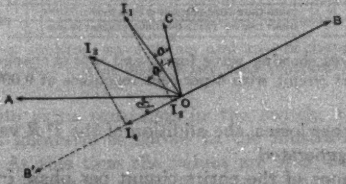
Trace No. 1—*A* phase current through short; scale 19,350 amperes per in.
2—*B* phase to neutral line bus pressure; scale 48,000 volts per in.
3—*C* phase to neutral line bus pressure; scale 56,100 volts per in.
4—*A* phase generator current; scale 17,100 amperes per in.
5—*A* phase substation current, scale 3,000 amperes per in.
6—*A* phase to neutral line bus pressure; scale 32,700 volts per in.

FIG. 39.—Oscillograms showing the effect of reactance coils plus generator neutral rheostat on the operation of a standard synchronous converter during *A* phase to ground short circuit on bus. Instantaneous relay on 60:1 current transformer controlling short circuit switch, Regular relay controlling unit switch

would flow an instantaneous current 60 per cent greater than the short circuit current of the machines. With 6 per cent reactance in series with each generator this would amount to 25,300 amperes. Without external reactance this would amount to 46,000 amperes assuming no saturation.

When external reactances are used, the drop across the reactance of the incoming machine might be as high as 13,000 volts. It is, therefore, doubtful if the reactance as designed would protect the generator entirely in case of very bad synchronizing. The 25,300 amperes is 60 per cent more current than on any short circuit and some of the short circuits while they did not harm the turbine, resulted in a fairly severe shock.

If five turbo-generators are running in parallel and an internal short circuit occurs on one of them it can be assumed its voltage drops to zero. The other four machines will then feed into it. The reactances in the generator leads and the other four sets of reactances will limit the current from the busses. Figuring the generator reactances as 4 per cent and the external reactance as 6 per cent the amount of reactance to limit the current will be 6 per cent + $\frac{1}{4}$ of 10 per cent or $8\frac{1}{2}$ per cent. The pressure across the terminals of the defective machine would be 9000 volts. Therefore the current that would flow would be 100/85 of 15,800 or about 18,600 amperes.



OA—Generator e.m.f.
OB—Counter e.m.f. of substation unit.
OB'—Negative vector of OB
OC—Resultant e.m.f. (of OA and OB) causing cross current to flow
OI_1—Cross current with small amount of reactance
OI_2—Active or synchronizing component of OI
OI_3—Cross current with larger amount of reactance in the circuit
OI_4—Active or synchronizing component of OI

FIG. 40

In order to find the maximum instantaneous kilowatts of turbo-generator No. 10 during short circuit, curves of the armature and field current were taken from representative oscillograms No. 317

and No. 318 and drawn to scale. These are shown in Figs. 41 to 44 inclusive. The curves show the armature and field currents for the first cycle during a three phase short circuit with 6 per cent external reactance at 9000 volts generator delta pressure.

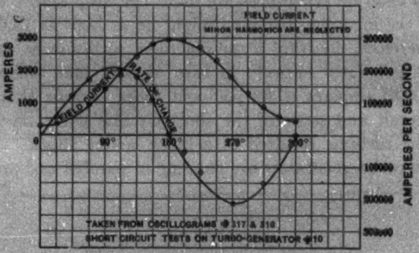


FIG. 41.—Curves showing wave forms and rate of change during a three-phase short circuit with 6 per cent reactance at 9,000 volts

Neglecting other losses, the addition of the $I^2 R$ values gives the total power generated.

The resistance of the entire circuit per phase included armature, reactance and oil switches, as measured was 0.033 ohms.

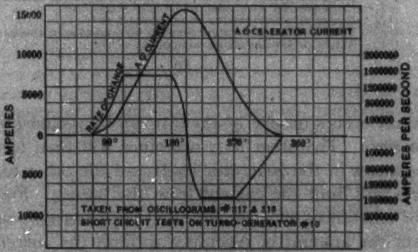


FIG. 42.—Curves showing wave forms and rate of change duringa three-phase short circuit with 6 per cent reactance at 9,000 volts

Oscillograms show, however, considerable drop across the oil switch used for short circuiting. This drop from a number of oscillograms corresponded to a resistance of 0.1 to 0.18 ohms. This value is not very accurate on account of the small deflection on the oscillograms measured. The oscillograms also show that this drop is not always directly in phase with the current. The resistance of the generator field circuit was 0.4 ohms, neglecting exciter resistance.

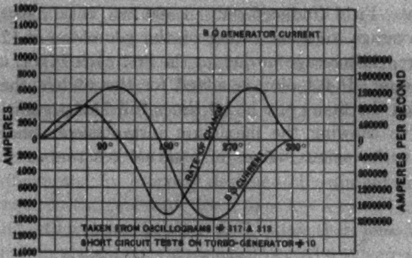


FIG. 43.—Curves showing wave forms and rate of change during three-phase delta short circuit with 6 per cent reaction of 9,000 volts

Assuming no extra resistance in the switch, the maximum instantaneous kilowatts as shown in the illustrations occurred at 190 deg. At this time the values are *A* ϕ, 8000 kw., *B* ϕ, 1320 kw. *C* ϕ, 2,670 kw., field (induced only) 2,720 kw., total

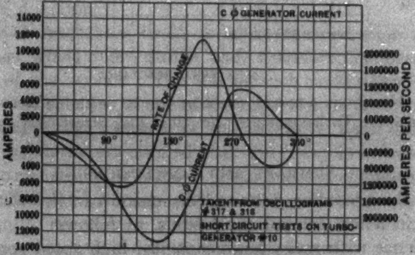


FIG. 44.—Curves showing wave form and rate of change during a three-phase delta short circuit with 6 per cent reactance at 9,000 volts

14,700 kw. The full load kw. is constant for a balanced load and is 12,000 kw. Therefore, the maximum instantaneous torque is 1.2 times the full load torque. If 0.1 ohm is added for the switch, the maximum instantaneous torque becomes 4.8

times the full load torque. This neglects the power supplied to the field by the exciter and the power losses due to the stray magnetic flux of the armature reaction.

The mean kilowatts during the first cycle as shown in the illustrations are as follows: *A* ϕ 1,940 kw., *B* ϕ 1,000 kw., *C* ϕ 1,440 kw. Field (induced only) 1,300 kw., total 5,680 kw.

The average kilowatt rating of the generator is 12,000 kw. Therefore, the average torque for the first cycle is 0.47 times full load torque. If 0.1 ohm is added for the switch, the average torque for the first cycle is 1.9 times full load torque.

A curve showing the maximum instantaneous short circuit current with various values of external reactances is given in Fig. 45.

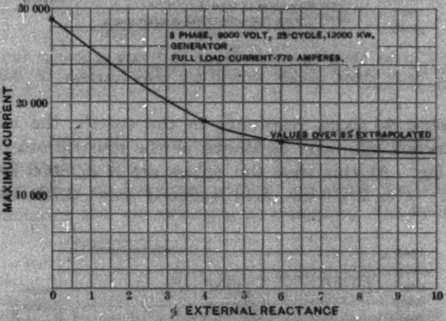


Fig. 45.—Maximum amperes on short circuit with different external reactances. Turbo-generator No. 10 at Fisk Street Station.

Summary and Conclusions

All of the preceding data and discussion can be briefly summarized in a few general conclusions, as follows:

Experience with many large capacity, high speed generators, indicates the need for reducing the possible current which may flow into a fault.

The tests indicate that the instantaneous short circuit current of these generators is actually not as high as has been thought but that this current, due to its comparatively high power factor, produces severe stresses on the generator and seriously strains the oil switches.

In order to reduce the severity of these strains and their wide spread effect in system disturbances, it is desirable to have a higher value of reactance in the generator circuit than many of these large capacity generators have been designed for. In the case of the 12,000-kw., 9000-volt, 750-rev. per min., 25-cycle units it appears that an external reactance of approximately 6 per cent is desirable. A lesser value than this does not reduce the current sufficiently and a greater value results in a very small increment of decrease. This is also true for the 6 per cent reactance with regard to the torque on the generator resulting from the short circuit.

Such reactances will limit the current to a value where it can be safely interrupted by properly designed oil switches and will keep the torque on the generator down to so low a value that even when feeding into a short circuit at the busbars there is no appreciable lessening in speed nor is the unit subjected to severe strains.

The use of the neutral rheostats at Fisk Street should be continued even after the reactances are installed as the combination of these two pieces of apparatus tends materially toward lessening the spread and severity of short circuits, which, in most cases at least, start as single-phase short circuits.

Operating experience, covering a period of about two years with reactances in connection with 5000-kw., 9000/20,000-volt transformers, shows these coils to be apparently very effective in the desired direction.

The use of reactances tends to make the operation of the system as a whole more stable and, therefore, increases the reliability of the service. The use of such coils, therefore, is apparently the solution of one of the most serious problems and as a result in a large measure of the extensive tests described above, we may now rest assured that the heavy investments already made and still to be made in power stations of great magnitude are secure, and that the safe-guarding of these very large capacity units, which have aided so materially in reducing the cost of the product, is a definite accomplishment.

Acknowledgment is due to the various engineers engaged on the tests, to Mr. E. B. Merriam and staff from the General Electric Company, Messrs. W. A. Durgin, N. J. Conrad, R. H. Whitehead and others from the Testing Department of the Commonwealth Edison Company and especially to Messrs. Durgin and Whitehead for assistance in working out the very complete set of results which permitted a proper correlation of the data and its presentation in this paper.

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The Use of Reactance Coils in Generating Stations. P. Junkersfeld. N. E. L. A. '09. *Electrical Age*, June, 1909.

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A paper presented at the 28th Annual Convention of the American Institute of Electrical Engineers, Chicago, Ill., June 27, 1911.

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SOME RECENT TESTS OF OIL CIRCUIT BREAKERS

BY E. B. MERRIAM

INTRODUCTION

Whenever an electrical circuit carrying considerable energy is opened in oil, gases are generated. These expand and rise, and tend to force the oil out of the containing vessel. They also form with air explosive mixtures, and either explode, or burn for a considerable length of time when ignited. It is important, therefore, that oil circuit breakers be provided with strong oil containing vessels in order that they may withstand the high initial stresses which are often present under certain conditions and also that suitable provision be made for retaining the oil.

In order to check tests made on moderate capacity circuits and to study the operation of oil circuit breakers and current limiting reactances on circuits of large capacity, under various conditions, arrangements were made through the courtesy of the management of the Commonwealth Edison Company of Chicago, Ill., to use one of its generating units as a source of power for tests.

APPARATUS

These tests were made at the Fisk Street Station (Fig. 1) during the early part of the year, using a three phase, 12,000-kw., 9000-volt, 25-cycle, turbo-alternator.

The following apparatus was made up at the factory and shipped for test:

3 current-limiting reactances, Fig. 2 (no iron core).

1 standard triple-pole type F form H-3 oil circuit breaker (8 in. diameter oil vessel).

2 special triple-pole type F form H-3 oil circuit breakers.

1 standard triple-pole type F form H-6 oil circuit breaker (10 in. diameter oil vessel).
3 standard single-pole type F form K-2 oil circuit breakers.

FIG. 1.—Interior of Fisk street station, Commonwealth Edison Company

1 special triple-pole type F form K-12 oil circuit breaker.
3 special single-pole type F form K-12 oil circuit breakers.

The connections are given in Fig. 3.

For the purposes of observation and measurement, use was made of two three-element electromagnetic oscillographs, one three-element arc length recorder, a special gas engine indicator, special spark gaps, movement recording devices, etc.

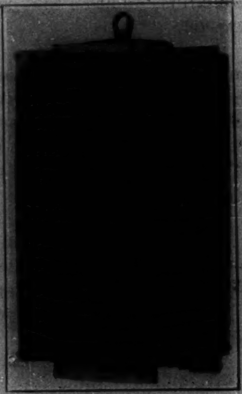

FIG. 2.—One unit of generator current-limiting reactances

METHOD OF TESTS

Practically all of the tests were either three phase or single phase short circuits, some to ground and some between phases. The short circuits were made by closing the triple pole type F form K 12 oil circuit breaker shown in Fig. 4.

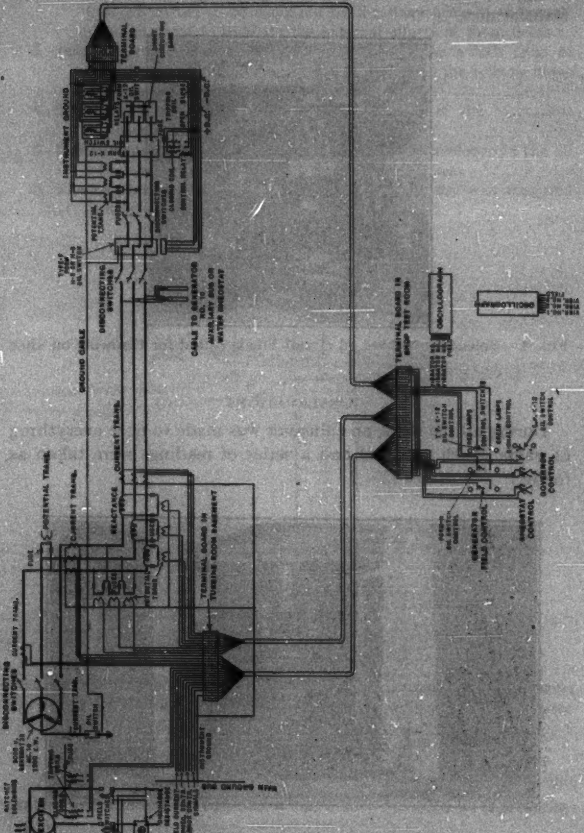
TERMINAL BOARD
INSTRUMENT GROUND
DISCONNECTING SWITCHES
GROUND CABLE
CABLE TO GENERATOR NO. 10 AUXILIARY BUS OR WATER RHEOSTAT
TERMINAL BOARD IN SHOP TEST ROOM
OSCILLOGRAPH
POTENTIAL TRANS.
CURRENT TRANS.
REACTANCE
TERMINAL BOARD IN TURBINE ROOM BASEMENT
EXCITER
FIELD
RHEOSTAT
GENERATOR FIELD CONTROL
GOVERNOR CONTROL
RHEOSTAT CONTROL

FIG. 3.—Wiring diagram of test circuits

The switch under test then automatically opened the circuit, being tripped by instantaneous relays operated from current transformers.

FIG. 4.—Solenoid-operated oil circuit breaker used for throwing on shor circuits

OBSERVATIONS

During all the tests, an endeavor was made to note everything of value which occurred and a series of readings were taken as follows:

FIG. 5.—Flashlight of generator current-limiting reactances during test No. 27

1. Oscillograms were made showing the relation between the currents and voltages of the various circuits, such as alternator armature current, alternator armature voltage, alternator field current,

alternator field voltage, voltage drop across reactances and voltage drop across oil circuit breakers.

2. Pieces of iron of small weight and size, placed at known locations were permitted to be displaced by the stray fields of the reactances in order to indicate the external efforts of these fields.
3. Thin strips of paper were attached to the reactance coils (Fig. 5) in such a manner as to make it impossible for the coils to move without tearing the strips.
4. Spark gaps were placed across the end turns of the reactances in order to detect any voltage rise.
5. Indicator cards were taken to show the stresses developed in the oil vessels of the various circuit breakers during test.
6. The length of arc in the oil circuit breakers under test was measured during test.

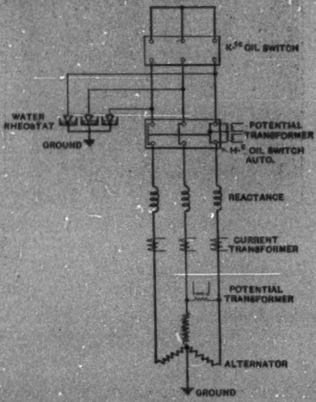

Fig. 6.—Diagram of connections for test No. 27

7. Speed records were taken of the various oil circuit breakers during test in order to permit analyzing the various arc length and pressure records.

Tests

Approximately 150 short-circuit tests were made during this series and the ones given below have been selected as representative.

Test No. 27. For this test, connections were made as in Fig. 6, the oscillograph vibrators being connected to the secondaries of the current and voltage transformers shown. It will be noted that a water rheostat was connected between the H-6 oil circuit breaker (Fig. 7) and the K-12 oil circuit breaker (Fig. 3). It should also be noted that the reactance in each phase gave a drop of approximately 312 volts at rated load current of the alternator, this being known as a 6 per cent reactance. An initial load of about 7500 kw. was placed on the alternator by the water rheostat and the K-12 oil circuit breaker was then closed, super-imposing a short circuit on the testing system. Oscillograms Figs. 8 and 9 show the events which then occurred and Fig. 10 shows the length of the arc and the stress which was developed near the wall of "A" phase generator oil vessel.

FIG. 7.—Type F form H-6 oil circuit breaker during test No. 27

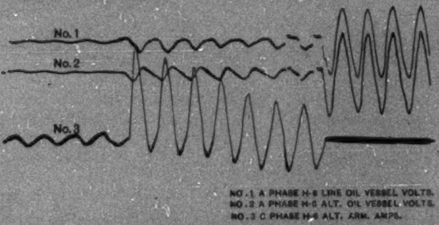

FIG. 8.—Oscillogram A test No. 27

During this test, some smoke came out of the oil vessels and a few drops of oil were drawn up by the switch rods along the inside of the bushings of the oil vessels and splashed out. The reactance windings were not displaced nor did the recording apparatus detect the slightest movement of the coils, although this was one of the worst short circuits recorded.

Test No. 32. Connections for this test are shown in Fig. 11. There was no initial load connected to the alternator and the circuit breaker under test was an H-3 having 8 in. diameter oil vessels fitted with the baffles shown in Fig. 12. As before, the oscillograph vibrators were connected to the secondaries of the voltage and current transformers and the shunt shown in the wiring. The short circuit was thrown on by the K-12 oil circuit breaker. The resulting oscillograms are given in Figs. 13 and 14 and the stress in the generator oil vessel of " A " phase, velocity of the oil circuit breaker contacts, and the arc length record are given in Fig. 15. Some oil and smoke came out of the H-3 oil vessels during this test. Besides this, the generator oil vessel in " B " phase was distended sufficiently by the pressure developed within it to permit its top to be forced out but without in any way injuring the threads. On examination, it was found that the expansion bolt in this top had not been tightened. The top was then replaced, the expansion bolt tightened and no trouble of this nature was recorded in any of the succeeding tests.

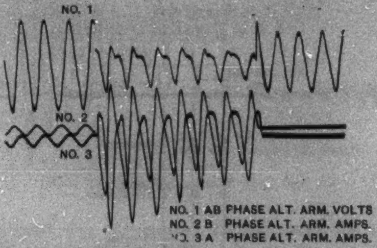

Fig. 9.—Oscillogram B test No. 27

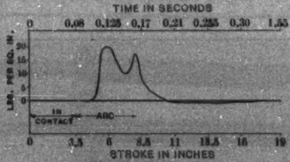

Fig. 10.—Arc length and pressure records test No. 27

Test No. 61. Connections were made as shown in Fig. 16. The reactance was changed so as to have only 4 per cent in series in each phase of the generator. The H-3 oil circuit breaker was fitted with oil diverters shown in Fig. 17 and as before, the oscillograph vibrators were connected to the secondaries of the current and voltage transformers and the shunt in the generator field. The oscillograms obtained are shown in Figs. 18 and 19 and the arc length, stress records, etc., are shown in Fig. 20, the speed curve being developed in Fig. 21. During this test, some oil and smoke came out of the oil vessels of the H-3 switch. Some burning gases came out of the "cuckoo door" of generator oil vessel in "C" phase and it was also noted that the door of this cell opened a little bit.

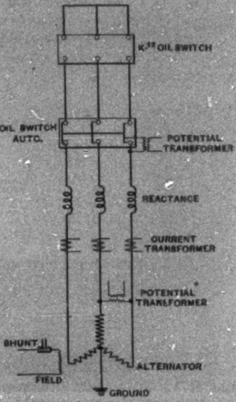
K-12 OIL SWITCH
H-3 OIL SWITCH AUTO.
POTENTIAL TRANSFORMER
REACTANCE
CURRENT TRANSFORMER
POTENTIAL TRANSFORMER
SHUNT
FIELD
ALTERNATOR
GROUND

FIG. 11.—Diagram of connections test No. 32

FIG. 12.—Baffle of H-3 oil circuit breaker used in test No. 32

Test No. 171. Connections for this test were made as in Fig. 23 and 6 per cent reactance was replaced in each of the phases. The triple pole type F form K-12 oil circuit breaker was made automatic and opened the short circuit which was thrown on the system by the three (3) single pole type F form K-12 oil circuit breakers. The resulting oscillograms are shown in Figs. 24 and 25 and the pressure diagrams and arc lengths in Fig. 25. During this test, some smoke and oil came out of the oil vessels but both were directed downward by the external diverters with which this circuit breaker was equipped. These proved very effective and did not permit the oil and gases to be thrown outward.

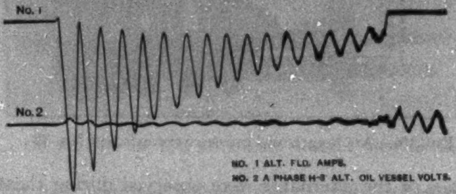

Fig. 13.—Oscillogram A test No. 32

Test No. 173. Connections for this test were similar to those shown in Fig. 23. The H-3 oil circuit breaker was made automatic and one phase fitted with an oil diverter. Short circuit was thrown on by the triple pole K-12 oil circuit breaker and the resulting oscillograms are given in Fig. 27, the arc length and stress diagrams being shown in Fig. 28. The action of the H-3 oil circuit breaker during this test is shown in Fig. 29. It is seen therefrom that some smoke and oil came out of "C" phase oil vessels and some smoke came from "B" phase oil vessels, while "A" phase oil vessels showed no external disturbance. For this test, the "A" phase oil vessels were fitted with oil diverter shown in Fig. 17, "B" phase oil vessels were fitted with a special oil diverter. "C" phase oil vessels were fitted with oil diverter shown in Fig. 12, thus giving a comparison of the action of these three schemes.

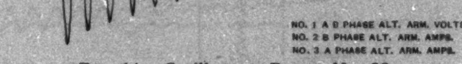

Fig. 14.—Oscillogram B test No. 32

EFFECT OF SHORT CIRCUIT ON GENERATOR

In tests of this nature, it has always been noted that the field current of the alternator rises when the armature is short circuited. Values as high as ten times field current at rated no load voltage of the alternator were observed during these tests and the form of these field currents is shown in Figs. 13 and 18. This phenomenon is dependent upon the inter-action between the field and armature coils, and the maximum value which the field current attains is dependent upon the co-axial relation of the two circuits and their electrical constants. It was also noted during this series of tests that spits of fire came out of the

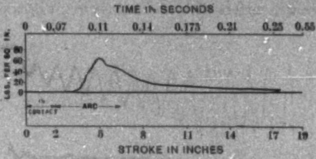

FIG. 15.—Arc length and pressure records test No. 32

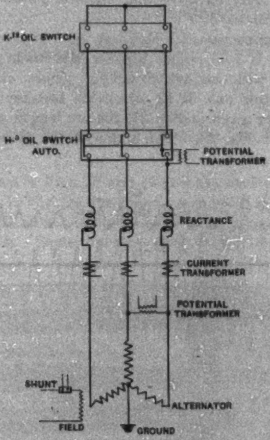
K-12 OIL SWITCH
H-3 OIL SWITCH AUTO.
POTENTIAL TRANSFORMER
REACTANCE
CURRENT TRANSFORMER
POTENTIAL TRANSFORMER
SHUNT
FIELD
ALTERNATOR
GROUND

FIG. 16.—Diagram of connections for test No. 61

alternator field. This has often been noticed in connection with high voltage transformers suddenly thrown on a live circuit and is doubtless due to the very high voltage induced in the alternator field windings when a short circuit current is established in the alternator armature. Our records show that this voltage can be as high as seven times normal, although it may have been considerably higher, since we only made a few measurements.

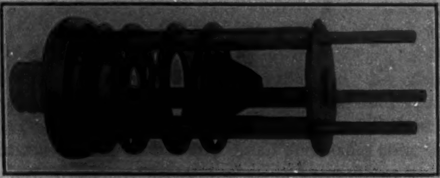

Fig. 17.—Oil diverter of H-3 oil circuit breaker used in test No. 61

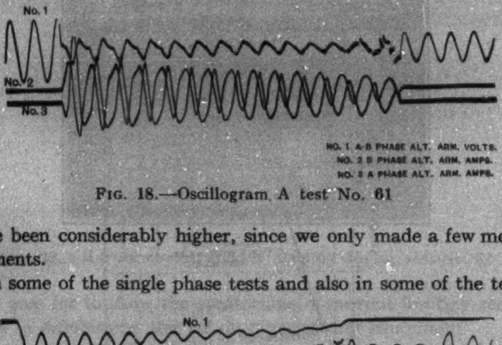

Fig. 18.—Oscillogram A test No. 61

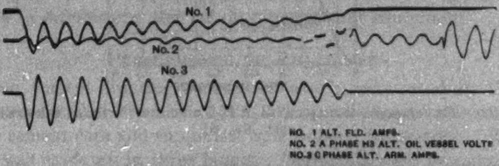

Fig. 19.—Oscillogram B test No. 61

In some of the single phase tests and also in some of the tests where the short circuit was thrown on by three (3) single pole circuit breakers, it was noticed that the voltage of the phase not short circuited rose to a very high value, some times as high as two and a half times normal. This was probably due to the very large current induced in the field, which, acting on the unloaded phase, produced a voltage rise.

The end turns of the alternator did not move during any of these tests, a rigid inspection being made at frequent intervals to detect any such movement.

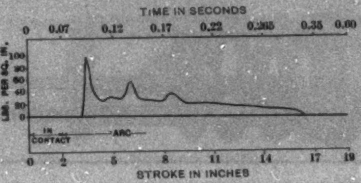

FIG. 20.—Arc length and pressure records test No. 61

There was no appreciable drop in the speed of the alternator when the short circuits were thrown on, probably due to the current limiting value of the reactances discussed later.

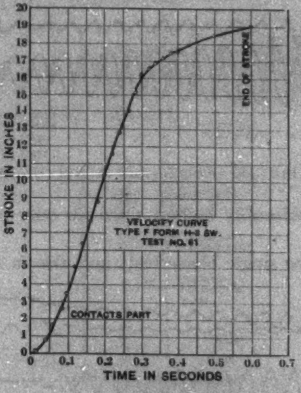

FIG. 21.—Developed velocity curve of H-3 oil circuit breaker taken during test No. 61

In comparative short circuit tests made with the throttle of the turbine open and with the throttle closed, practically the same currents were produced in the test circuit.

A number of tests were made by grounding one or all of the three phases of the circuit. In all such cases, it was noted that the effects, as instanced by the action of the oil circuit breaker under test, were very much more violent than when the short circuit was between phases. It was also noted that when the water rheostats were connected to the test circuit as an initial load, their neutral point also being grounded, the effects were very much more violent than when this initial load was absent.

At the completion of the tests, the generator was immediately placed in commercial service and is still operating, none the worse for the severe service demanded of it throughout this series.

FIG. 22.—H-3 oil circuit breaker opening during test No. 61

This goes far to show the great value of current limiting reactances in diminishing the jar on a generating equipment.

PERFORMANCE OF REACTANCES

The current limiting reactances which were used in these tests consisted of 76 turns of 1,000,000 cir. mil copper cable wound on a cement core and supported by a wooden framework. Each coil was made up in three layers. Terminals were brought out at the top and bottom. The result was a cement cored reactance having no iron in or about it. This construction was employed since the introduction of iron would not appreciably increase the current limiting value of the device. It was also found with the particular generator under test that the introduction of

6 per cent reactance in each phase halved the maximum instantaneous current and reduced the torque on the turbine shaft to about one seventh of what it would have been without the reactance. In mentioning 6 per cent reactance, it should be recalled that this refers to the drop across the reactance, which, with rated load current through it at rated frequency, would be 6 per cent of the rated phase voltage of the alternator. The reactances also maintained the terminal voltage of the alternator when a short circuit was thrown on the system beyond the reactances, and permitted the generator to recover its normal voltage after a short circuit had been removed much more rapidly than would have been the case had the short circuit been placed directly across its terminals. This makes them of great importance where a synchronous load is connected to a system since one of the two features for holding a synchronous load is the maintenance of voltage.

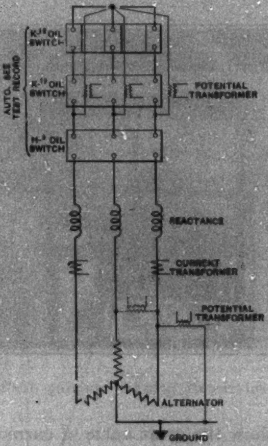
K-12 OIL SWITCH
AUTO. SEE TEST RECORD
K-12 OIL SWITCH
POTENTIAL TRANSFORMER
H-3 OIL SWITCH
REACTANCE
CURRENT TRANSFORMER
POTENTIAL TRANSFORMER
ALTERNATOR
GROUND

FIG. 23.—Diagram of connections for tests 171 and 173

As a result of the reduction of the torque on the turbine due to the introduction of reactances, there was practically no drop in speed when a short circuit was thrown on it. Hence, the frequency of the system was maintained at practically normal value, and this, together with the maintenance of the alternator voltage, as previously described, tended to markedly improve the operation of synchronous apparatus under abnormal conditions.

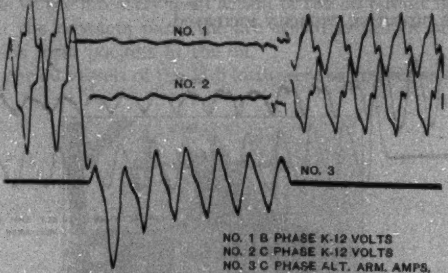

Fig. 24.—Oscillogram A test No. 171

Current limiting reactances also change the power factor of a short circuit and distort the wave form of the system as may be seen on comparing the first parts of curves 1 and 2 in

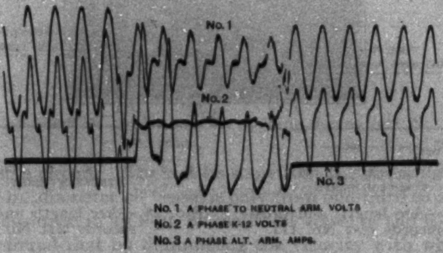

Fig. 25.—Oscillogram B test No. 171

Fig. 25. The stray fields of these reactances were not sufficient to distort the coils in any way and at a distance of several feet, iron screens were not noticeably attracted nor were they appreciably heated.

ACTION OF OIL CIRCUIT BREAKERS

In the discussion of various tests, it was noted that at times some oil was thrown out of the oil vessels. By suitable baffling, the energy imparted to the oil by the expansion and explosion of the gases generated in the oil vessels was absorbed and the operation of the circuit breaking device materially improved and its rupturing capacity increased.

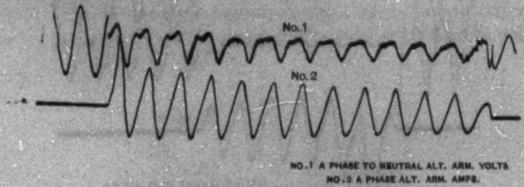

FIG. 27.—Oscillogram test No. 173

It was also found possible to separate the gases from the oil, thereby permitting the gases to escape into the air and the oil to be retained in the oil vessels.

In a commonly constructed design, a small distortion of the oil vessels permits a considerable quantity of oil to be thrown out. This, however, can be readily prevented.

It is very often found convenient to install oil circuit breakers in fire resisting compartments. By means of external oil diverters, it was found possible to direct the gases and oil thrown out of the oil vessels to the lower parts of the cells. In reported cases on other systems, gases from oil circuit breakers have been known to ignite, resulting in an explosion. Suitable baffles and diverters can be designed, however, to take care of these conditions.

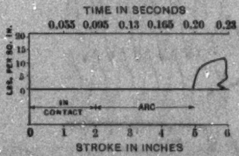

FIG. 26.—Arc length and pressure records test No. 171

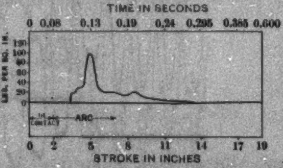

FIG. 28.—Arc length and pressure records test No. 173

In all of these tests, the temperature of the oil was roughly noted and in no case was it found to have been raised an appreciable amount after short circuit was opened. In some recent tests where successive short circuits were opened by oil circuit breakers (some times as many as six in ten seconds) it was also found that the oil did not heat appreciably. It is thought that this is due to the intensely local action of the oil circuit breaker, for, when the contacts part, the arc which is drawn produces gases which form pockets in the oil.

The larger oil vessels of the H-6 form were of greater assistance in opening a circuit. The results show that the stress developed in the 10-in. diameter oil vessel is only from one-third to one-fifth of that developed in an 8-in. diameter oil vessel of the H-3 form.

FIG. 29.—H-3 oil circuit breaker opening during test No. 173

It was found that by diminishing the velocity with which the contacts parted, there was more disturbance and the rupturing capacity of the device was greatly diminished.

The length of break is directly connected with the velocity of moving contacts. A long break is very desirable in as much as it gives a large factor of safety under normal operating conditions and a much greater rupturing capacity in emergencies.

A preliminary review of these tests shows that the oil circuit breakers opened all of the loads or short circuits without producing any external disturbances or developing any undue pressures, and their ultimate rupturing capacity was not reached. The main current carrying parts were well protected from burning by the arcing contacts and these latter were not materially injured after opening and closing numerous short circuits. The temporary cell structure, although made of inflammable materials, was not injured in any way, and practically no stresses were developed in the cells.

During some of these tests a small quantity of oil came out of the oil vessels, was deposited on the cell doors and spreading out very thin gave the impression of a larger amount. By actual measurements after a number of severe short-circuits it was found that only 5 per cent of the oil had been lost. The repeated use of the oil in the oil vessels did not appreciably diminish its efficiency and the introduction of suitably designed oil baffles and diverters overcame the tendency for the oil to come out of the oil vessels. The oil diverters and baffles experimented with can be readily applied to existing circuit breakers at comparatively small expense and with practically no changes to the original installation.

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DEVELOPMENT OF THE MODERN CENTRAL STATION

BY CHARLES PROTEUS STEINMETZ

The predecessor of the huge modern central station is the Edison direct-current three-wire station, which was developed 20 years ago. By a system of feeders and mains, direct current was distributed at 220-volts from a station located at the center of power demand. When the limit of economical distribution from a single station was reached, additional stations were built, and all the stations connected by tie-lines.

Characteristic of these stations were the good voltage regulation, incident to the system of feeders and mains; the high economy, resulting from the parallel operation of all the stations and the consequent reduction of light load losses to a minimum, and the high reliability of service, which stands unexcelled even to-day, and which resulted from

a. The parallel operation of all the stations, which guarded the system in case of breakdown of one or several stations;

b. The storage battery reserve, which maintained service even at a complete shut down of all the generating stations, and especially

c. The nature of the system of low tension feeders and mains, which limited the effect of any breakdown at any point of the system to its immediate vicinity, by limiting, by the resistance of feeders and tie-lines, the power which could be concentrated at any point, to such an extent, that no local breakdown could involve, or even seriously affect the entire system.

It must be conceded that in this latter respect this low-tension system was safer than even the present modern high-voltage generating systems, and in the latter the problem of the localization of the effect of any breakdown is still the most important one in the development of the modern central station.

The most serious disadvantage of the direct current three-wire generating station was the limited distance to which power could be transmitted economically at 220 volts. This limited the use of the system to densely populated districts; as the interiors of large cities were within the economic radius of 220-volt distribution a load for a generating station of economical size could be found. It also did not permit the best economy of operation, as it required the location of the generating stations in the interior of the cities.

The limitations in the distance of transmission were soon overcome, and electric power made generally available, by the alternating-current system. As it was first developed, as single-phase high-frequency system with individual transformers at the customers' premises, it had the fatal defect of large all day losses in the transformers, and as the result, most of these early alternating-current stations were not an economical success, and the alternating-current system became economically feasible only by the introduction of the three-wire-secondary mains, fed from large transformers by primary feeders, that is, the main features of the Edison feeder and main system, from which the modern alternating current system differs only by the substitution of high-tension feeder and transformer, for the low-tension feeder of the direct-current system, and by the addition of a fourth wire or other method (as separate feeders), to take care of power distribution to motors.

The final power supply to the customers, for lighting or other domestic services, is now generally from a three-wire 220-volt main, by direct current in the interior of large cities, by alternating current in less densely populated districts. The characteristics which make the direct-current systems suited for more concentrated, the alternating-current system for less concentrated demands, are:

Reactive drop and magnetic screening are absent with direct current, and large conductors can thus be used, carrying larger currents than are economical with alternating distribution. A greater density of load can thereby be taken care of, larger power supplied over each feeder, and voltage regulation at every feeding point in the mains thus becomes economically feasible. The mains, tied together, exchange power between feeders, and thereby equalize the voltage. Storage battery reserve is conveniently feasible, with its great increase in the service reliability. For certain classes of service, as high speed elevators, the direct-current motor is further developed. However, the low-tension direct-current feeder must be carried back to a generating station or converter substation.

With alternating-current supply, 2200-volt high-tension feeders can be used, and a much larger territory thereby supplied from one station. Much lower voltage drops are feasible in the high-tension alternating-current feeders, than in the low-tension direct-current feeders, and several transformers with their secondary mains can thus be supplied, with fair regulation, from the same primary feeder, and this allows the installation of small mains of limited extent. The secondary mains may be sectionalized without serious disadvantage in regulation. The high efficiency of the modern transformer permits economical power supply in districts which can not be reached by direct current, as the load is so scattered that only a moderate amount of power is accessible to each main, and sufficient load for the economical operation of a converter substation could not be found within the economical radius of such a station.

The economic disadvantage of the location of a number of direct-current generating stations in the interior of large cities led to their replacement by converter substations, which receive their power from a large three-phase generating station, usually at 25 cycles. Thus originated the present system of monster three-phase power generating stations, which supply numerous converter substations for 220-volt underground direct-current distribution in the interior of the cities, with storage battery reserve; supply transformer or frequency converter substations for 2200-volt alternating primary distribution in the less densely populated districts, 600-volt converter substations for railway, and supply three-phase 25-cycle power direct to large motors. Reliability insurance against a serious breakdown in the generating station led to the subdivision of the power generation in two or more main generating stations, and so we see now in operation in this country huge generating stations, coöperating with each other and with smaller outlying stations, very similar in principle, though vastly greater in magnitude, than the direct-current three-wire generating stations of 15 years ago. To the former direct-current generating stations thus correspond in the present central station development not the converter substations of the direct-current distribution section of the system, but the main three-phase generating stations, and to the 220-volt feeders and tie-lines between the stations correspond the 6,600-, 9,000- or 20,000-volt power feeders from the main generating stations to the substations, and the tie-lines between the generating stations.

Comparing the modern system of high voltage three-phase generating stations, which supply power to a large city and almost to a state, with the system of low voltage direct current generating stations of old, we find, besides the vastly greater amount of power of the modern system, and correspondingly greater destructiveness of the power when beyond control, two essential differences:

a. The alternating nature of the power involves in the parallel operation of the generating stations, as required by economy and reliability, the problem of synchronizing, which did not exist with the direct current stations.

b. While in the direct current system the power, which could be developed at any point in the system, was limited by the resistance of feeders and mains, and the limited power of the generators, and an accident anywhere in the system could not seriously involve the entire system, but remained essentially local in character, in the present system the maximum power is available practically everywhere, and an accident or disturbance may be felt over the entire system. That is, the safety resulting from the locally limited power, and corresponding reliability, of the direct-current system, is not inherent in the modern high-power and high-voltage alternating system, and before the operation of the present huge systems can be as safe and as reliable as that of the low-tension direct-current systems was, means must be found to limit the power which can be developed in case of accident anywhere in the system, to a safe value, that is a value which would not seriously affect or endanger the operation of the system.

The safety of the low-tension direct-current system against general disturbances caused by a local accident, such as a short circuit, was the result of the relatively high resistance of circuits; it was however paid for by a lower efficiency of distribution, resulting from the losses in the line, such as are no longer permissible in our modern large systems, and if permissible, would not be feasible, as the distribution cables could not dissipate the power without self-destruction. However, due to the alternating nature of the power, voltage can be consumed in the modern systems, and the current limited thereby, without corresponding loss of power, by reactance; and to make our modern high-voltage high-power systems as safe against local accidents, as were the low-tension direct-current systems, power-limiting reactances must in the former take the place of the resistance of lines, feeders and mains of the latter system.

The industry has been slow to realize the importance of reactance in giving safety and corresponding reliability to high-power generating systems. The reason was a prejudice against reactance, which had survived from the early days of the single-phase high-frequency systems, in which the reactance in generators, lines and transformers had been the enemy which spoiled the desired voltage regulation. We are just beginning to realize now, that in the huge systems which use a large part of their power by synchronous machines, as converters, frequency changers, etc., reactance is not an enemy to regulation, but affords the most effective means of voltage regulation by phase control.

A considerable amount of reactance is necessary for safety, to limit the possible local concentration of power, and for voltage regulation in systems containing synchronous machines, and also for the stability of the latter, as the parallel operation of synchronous machines, whether generators, motors or converters, is possible only if the circuit between the machines contains considerable reactance.

In a station or group of stations of 100 to 200 megawatts generator capacity, in high-speed turbo alternators—and there are a number of such stations now in existence—with a momentary short circuit current of 30 to 40 times full load current, the maximum current which could momentarily appear at a short circuit on the bus bars, would correspond to from three million to eight million kilowatts. When opening such a short circuit, the power at the opening break must pass from zero at short circuit to zero at open circuit, over the maximum momentary output of the generator, which is one-half the product of short circuit current and open-circuit voltage, or from one and one-half to four million kilowatts. It is obvious that no switching mechanism can be designed which can always be relied upon to open such power, and which at the same time is sufficiently small and reasonable in cost, to employ hundreds of them in the system, on the generators, feeders, etc. Hence the insertion of power-limiting reactance in generators, busbars, etc., becomes necessary for the safety of the system.

The low-tension direct current generators of old probably gave a momentary short circuit current of three to five times full load current, and at permanent short circuit lost their excitation. The modern high efficiency turbo-alternator gives from three to five times full load current on permanent short circuit, but nearly 10 times as much momentarily. While the permanent short circuit current is within safe limits of the mechanical and electrical strength of modern apparatus, the momentary short circuit current is not, but, allowing for the advance in the art of machine design since the days of the low-tension direct current machine, a momentary short circuit current of 10 to 12 times full load current would be within safe limits. This means increasing the self-inductive reactance of the generator to 8 to 10 per cent. It can either be done by the insertion of external reactance, preferably in the phase leads, or by the design of the generator, or by both. Internal reactance of the generator of the required amount interferes with economical design, and has the disadvantage of offering no protection in case of an internal short circuit which eliminates the generator reactance, and the preferable method thus is to give the generator a reasonably high internal reactance (3 to 5 per cent) and insert additional reactance in the phase leads, of 4 to 6 per cent* Where step-up transformers or auto-transformers are used, they can be designed to afford the required external reactance.

Even when limiting the momentary short-circuit current of the generators to 10 times full load current, with the parallel operation of a system of several hundred megawatts generator capacity, the momentary short circuit power would still approach millions of kilowatts. It therefore becomes necessary in these large systems, either to operate the system in a number of separate sections, or to sectionalize the busbars by power limiting reactances.

The former is frequently done, but appears to me a temporary expedient only, and economically impracticable as a permanent condition of operation. When limiting the generator capacity per section to a maximum of 60 megawatts, three or four sections would be required in some of the existing systems. As this means a partially loaded generator in every section, a larger total generator capacity is required, and a lower economy of operation results, than with parallel operation of the entire system. Furthermore, reliability would require to supply every substation from several sections, and this would necessitate to sectionalize also every substation on the alternating side, and would thereby lower the economy of the use of feeders and substations. The necessity of providing means of throwing substation apparatus from one section to another section, in case of accident to one section, complicates the method of control and introduces the danger of accidentally connecting together in the substation feeders coming from different sections and out of synchronism with each other, with the result of a short circuit between two sections. As the complication of control would usually make it impracticable to carry feeders from more than two sections into a substation, the reliability of service would be lower than in parallel operation, when important substations could receive power from three or more power houses. The loss of economy and of reliability, and the complication of control of the system increase so rapidly with the increasing number of separate sections, that it appears to me, that the only feasible method, which permits unlimited extension of the system without any increase of danger and complication, is the parallel operation of the entire system, on a single ring bus, which is divided into sections by power limiting busbar reactances.

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*These power-limiting reactances must maintain their reactance at short circuit. Thus, if iron is used in them, the densities must be so low that saturation is not reached with the short circuit current. With a 4 to 6 per cent reactance, this limits the iron density to $B = 500$ to 1000, and as such low densities can far more economically be produced in air, the power-limiting reactances are ironless reactances.

These reactances must be large enough to limit the power which can flow over them, so that in case of a short circuit on one section, the adjoining busbar sections are only moderately affected, the further busbar sections not affected at all; at the same time, the reactances must be sufficiently low and of sufficient capacity, that any amount of current, which during a change of load a busbar section may draw from the adjoining busbar sections, can be safely transmitted over the reactances without any voltage drop, by a slight phase displacement between the adjoining busbar sections. With a capacity of 50 to 60 megawatts per section, a permanent carrying capacity of each busbar reactance, of two megavolt-amperes, at 15 deg. phase displacement, and a power limit, in case of a short circuit on one section and full voltage on the adjoining section, of 40 megavolt-amperes appears at present the best compromise. The ring bus, into which all the generators *G* of the system feed, would then comprise the busbars *B* of the various power houses, H_1, H_2 . . ., and the tie-lines *L* between the power houses, as indicated diagrammatically in Fig. 1, in which *x* denotes the power-limiting reactances in the generator leads, *x′* the power-limiting busbar reactances, *F* the feeders which issue from the busbar section, and *C* denotes the non-automatic, *A C* the automatic circuit breakers in the system.

Coming now to the consideration of the feeders which issue from the generator busbars. In the low-tension direct current system, the effect of a short circuit in a feeder—if not extremely close to a generating station—was limited by the resistance of the feeder. With the modern high-power alternating system, the feeder resistances are very low, and a short circuit in a feeder is almost a short circuit on the busbar. While generator reactances and busbar reactances greatly limit such a short circuit, there still remains the disadvantage, that nothing limits the power which is available locally on a feeder, below that available on the busbar to which the feeder connects, and in this respect the modern system is inferior to the old low-tension direct-current system. The safest method would be to limit

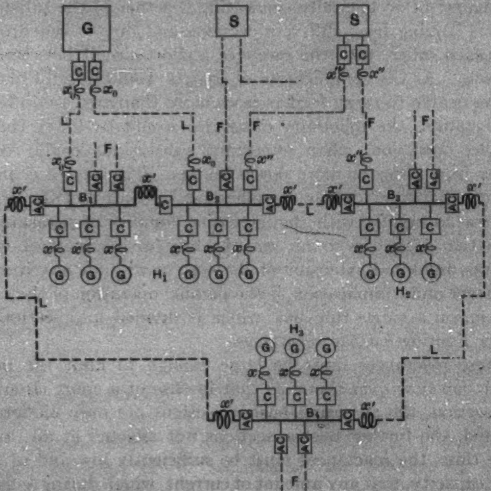

Fig. 1

the available short circuit power of every feeder by reactances at either end of the feeder, in the generating station and in the substation *S*, as indicated by x'' in Fig. 1. This method, which would make the modern high-power system as safe as the former low-tension direct-current system, has not yet been considered, since unfortunately the development of the alternating part of the present system has started from the experience of the small alternating systems of old and not from that of the low-tension direct current system, and in the former, the limited power of the generating system, combined with the relatively high reactance of the overhead feeders, made power limiting reactances in the feeders unnecessary. Instead of limiting the power, automatic circuit breakers are provided in the feeders, as indicated by *A C* in Fig. 1, which instantaneously cut off the feeder in case of short circuit. This method has been very successful, and with the limitation of power by the reactances in busbars and generators, appears sufficiently safe, but still has the disadvantage of momentarily exposing the busbar section and the feeder switches to the shock of short circuit in case of a failure of the feeder, and it may thus well be considered, whether a safer way of operation would not result from limiting the power of the feeders by reactances and then hold on to the feeder in case of a fault, until the fault either clears itself, or the feeder has to be cut off, that is, in other words, to return, even in this last structural element of the modern station, to the well tried principle of the low-tension direct-current system.

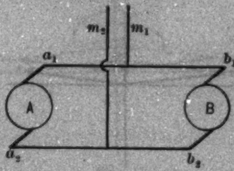

FIG. 2

In the parallel operation of the individual generators, and the entire generating station of the modern high voltage alternating-current system, a problem is involved, which did not exist in the direct-current system, *viz.*, synchronizing. The general problem of synchronous operation is well understood and is as follows:

If two machines, *A* and *B* in Fig. 2, (whether generators, synchronous motors, converters or frequency changers) shall run in synchronism, the constants of the circuit between the two machines, $a_2\ a_1\ b_1\ b_2$, must be such that any phase displacement (that is, position displacement) of the two machines causes a current to flow between the machines, which accelerates the lagging, retards the leading machine, irrespective whether in addition to the exchange or cross current between the machines, the machines also send out current, or receive current from the outside, at m_1 m_2. If the two machines are exactly in step, in the local circuit a_2 a_1 b_1 b_2, the voltages of the two machines, are in opposition, as shown by a and b in Fig. 3. Thus there is no resultant voltage, and no current flowing between the machines. If now the two machines are slightly out of step, and B lags slightly, that is, its voltage reaches the maximum at a slightly later time, b in Fig. 4, and A leads slightly, that is, its voltage reaches the maximum at a slightly earlier time, a in Fig. 4, the two voltages a and b in Fig. 4 give a resultant, which reaches its maximum midway between a and b, as shown as c in Fig. 4. This resultant or cross voltage of the two machines produces a cross current circulating between them. If now the circuit between the two machines, a_2 a_1 b_1 b_2, should contain only resistance, but no reactance, the cross current i would be in phase with the cross voltage c, as shown in Fig. 5. It would then be practically in quadrature with the two machine voltages a and b, that is, would be a wattless current in the two machines, neither consume nor produce power, that is, there would be no synchronizing power.

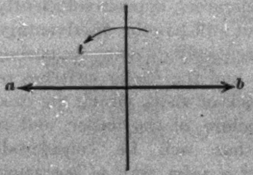

FIG. 3

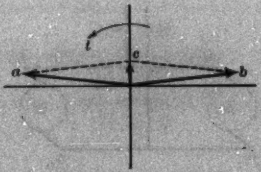

FIG. 4

Assume now that the resistance of the cross circuit is negligible compared with the reactance, then the cross current i would lag nearly 90 deg. behind the cross voltage c, which produces it, as shown in Fig. 6. Thus it would be approximately in phase with a, approximately in opposition with b, and would thus consume power in the leading machine A, that is, retard it, and supply power to the lagging machine B, that is, accelerate it, and thus pull the two machines together, as synchronizing current. Hence, the reactive or quadrature component (with regard to the cross voltage c) of the cross current is the synchronizing current, and the power component of the cross current exerts no synchronizing power. Thus, reactance is necessary for synchronous operation, and the larger the reactance is, compared with the resistance of the cross circuit, the larger a part of the cross current is synchronizing current. Increasing reactance therefore increases the synchronizing power. There obviously is a limit hereto: with increasing reactance, the cross current decreases, and while the percentage of the cross current, which is synchronizing current, increases, the absolute value of the synchronizing current, and with it the synchronizing power, again decrease.

For stable parallel operation of synchronous machines, a reactance of the cross circuit thus is required, which should be at least twice the resistance of this circuit.

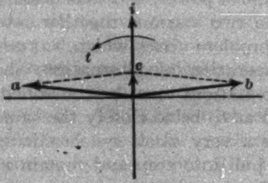

FIG. 5

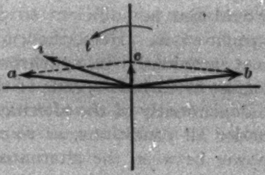

FIG. 6

Of the synchronous reactance of an alternator, essentially only the true or self-inductive component comes in consideration in synchronous operation, as the armature reaction component is usually too slow to exert itself. In steam-turbine alternators, the self-inductive armature reactance is very low, frequently only 2 to 3 per cent; however the armature resistance is a fraction of one per cent, and when connected to the same busbars, synchronous operation of such generators is satisfactory. A few per cent of resistance between the turbo alternators, as may exist when operating two power houses together over a tie-line, makes synchronous operation unstable or impossible without the insertion of a corresponding amount of reactance. This is to be kept in mind in the parallel operation of power houses, the more as the tie-lines are usually underground cables, and as such have practically no reactance. With power-limiting reactances in the generator leads, obviously a much higher resistance in the tie-lines between power houses would be permissible before parallel operation becomes impaired and additional reactance is required.

Parallel operation of synchronous machines thus requires reactance in the circuit between the machines. It is further required, however, that the combined effect of resistance and reactance, that is, the impedance of the cross circuit, is sufficiently low to allow a large enough current to flow to keep the machines together against any tendency which separates them, as inequality of the driving power, slighly different speed adjustment of the engine governors, etc. That is, the possible cross current between the machines must be comparable in magnitude with their full load current. This however is frequently not possible in the parallel operation of power houses distant from each other, over tie-lines. The capacity of the tie-lines between big power stations would economically be proportioned to the required exchange of power, and thus usually would not be sufficient to pull the two stations together into synchronism. Here, then, a new problem arises which was not met previously in synchronous operation of alternators: the engine or turbine speeds of the two stations must be controlled, independently of the alternators, so as to be so closely the same under all conditions, as to require a very small synchronizing power between the alternators, to pull into step and remain in step. That is, as we may express it, the prime movers must be synchronized. While this had not been done before, it is a mechanical problem, which electrically can be solved without serious difficulty, for instance, by controlling the governor in the steam supply by the power exchange between the stations, in combination with sufficiently powerful dash-pots, to guard against governor hunting.

An important application of this problem of electro-mechanical synchronizing will occur in the parallel operation of outlying stations, with the main station.

For instance, if at the end of a long feeder the power demand increases so greatly as to warrant the installation of a moderate sized station—one or two 2- to 5-megawatt turbo alternators—economy and reliability of operation would require this outlying station to be paralleled with the main generating station, so as to use the main station as reserve; and the economical method of operation would be to run the outlying stations as nearly at constant full load as possible, and take care of the load fluctuations by the main station, over the tie-lines, to get the benefit of the diversity factor of the entire system. This usually means not only a fluctuating flow of power in the feeder from the main station to the outlying stations, but often also a reverse flow. Voltage regulation at the outlying stations then can be accomplished only by phase control of the feeder, through reactances, as indicated at x_0 in Fig. 1, and with the increase of the outlying load the feeder capacity very soon would be insufficient to pull the outlying stations into step, and mechanical synchronizing, as discussed above, becomes necessary. We must realize, that in the direct line of the modern central station development is an extension of the power supply to that of an entire state or a number of states, from a few huge main stations near the centers of power demand, and numerous smaller outlying stations, with the entire system operating in synchronism through feeders and tie-lines, in which the power flow fluctuates in amount and in direction, and of which very few are sufficient to pull stations together into synchronism, but just sufficient to keep them in synchronism, if the speed regulation of their prime movers is independently maintained very closely the same.

These then are the two problems before the modern central station: The localization of any disturbance by power limiting reactances, and the synchronous operation over lines of limited power, by speed control of the prime movers.

DISCUSSION ON "THE USE OF POWER LIMITING REACTANCES WITH LARGE TURBO-ALTERNATORS," "SOME RECENT TESTS OF OIL CIRCUIT BREAKERS" AND "DEVELOPMENT OF THE MODERN CENTRAL STATION." CHICAGO, JUNE 27, 1911.

John W. Lieb, Jr.: Once again we are indebted to Dr. Steinmetz for a splendid and acute analysis of what is essentially a practical problem. With that keenness of discernment which we have been accustomed to expect from Dr. Steinmetz, he has touched upon a number of vital points which are of momentous interest to the present and the future of central station work. In the papers of Messrs. Schuchardt and Schweitzer, and in the paper of Mr. Merriam, we have notable instances of the method of applying scientific research to the investigation and solution of electrical problems, and the Institute is to be felicitated in having before it the details of these tests as affording material for thought.

In Mr. Schuchardt's paper he refers to the points to be determined by the tests which were made, indicating as the first, the instantaneous short circuit current of turbo-generators without external reactance. These questions referred to by Dr. Steinmetz and the other authors are matters which have been given careful consideration by the New York Edison Company, for instance, as another of the companies having these large problems to deal with, and this first element was one of the first questions which presented itself for investigation; and it was found that there was a considerable and wide variation as between types of generators, particularly turbo-generators, in this matter of internal reactance. There were tests made between types of generators as to the amount of internal reactance, amounting to as great a difference as two to one. It has therefore, opened a new light as to the possibility of control within the generator itself of the application of an increased amount, by and within the practical limitations which, the applications permits, of internal reactance, and by an increase of internal reactance you make it possible to limit the amount which need be applied externally.

It is difficult to conceive of the tremendous disturbance that takes place on a large interlaced system by short circuits in feeders or failure of generators. With ten, twenty, or thirty substations distributed over vast areas, having hundreds of synchronous machines working in parallel, the disturbance and throwing out of synchronism of this vast number of units, and the enormous difficulties involved in starting up these different substations widely separated, present unique problems, and it is therefore well worth most careful consideration to reduce the possibilities and the effects which these enormous concentrations of power in local disturbances may call forth.

The concentration of power for economical reasons in these huge power plants, the dependence for vast industrial enterprises and for our transportation systems, as well as for lighting and industrial power, make it absolutely essential that they shall be protected against disturbance, and that every possible precaution should be taken, which experience or ingenuity can provide, against irregularity in operation, because if these huge systems are going to be subjected to disturbance and interruption of service, we shall have reached a point where something radical will have to be done; but very fortunately with these elements which are brought before us, and other elements which are not here referred to, we can feel sure that the future provides fairly safe guarantees against interruption of service which produce very serious results in a community served by these vast enterprises. I am sure that we are very much indebted to the gentlemen of the Commonwealth Edison Company for having laid before us in great detail the results of their tests and experiments, with a view to arriving at a satisfactory solution of these problems, and to Dr. Steinmetz for having put his finger on the essentially important elements which are such prime factors in the development of the modern central station industry.

M. H. Collbohm: Mr. Merriam has presented us with very valuable data on the operation of oil switches designed for severe service conditions which data have been obtained from actual tests.

I note, however, that all these tests have been made on an oil switch type employing the vertical break. It would have been very instructive if the test had also been made on a switch of the horizontal break type in order to allow comparison between these different constructions.

It seems to me that the horizontal break oil switch would offer greater prospects for successful operation under severe conditions for the following reasons:

1. The break occurs in the lower part of the tank with a considerable head of oil above the break, in contradistinction from the vertical break where the arc starts nearer to the surface of the oil. This seems to be of great importance considering that the arc is most vicious at the moment of separation of the contacts when the current has its greatest value.

2. The horizontal movement of the thin switch blade through the oil combined with the tendency of the arc to rise vertically causes this arc to continually come into contact with fresh and cool oil layers thus extinguishing the arc sooner than would be possible in the vertical break switch where the arc tends to maintain its original vertical position. The break in the vertical type must therefore be considerably longer thus rendering this type of oil switch materially more expensive for the same rupturing capacity.

3. The knife blade form of contact pieces insure a more positive contact in the clips than can be obtained by the wedge or butt contacts usually employed in the vertical break switch for higher voltages.

The speaker has had experience with both types of switches on high tension lines and feels it his duty to express his satisfaction with the cheaper horizontal break oil switch which has opened without trouble several short circuits without the dampening influence of reactive coils.

The main advantage claimed for the vertical break type, *viz.*, the opening by gravity does not seem to the speaker to be superior to the opening by springs. The latter can be adjusted for a more rapid operation thus increasing the effectiveness of the switch. The gravity break type in the speakers experience in one instance failed to establish good contact in closing resulting in the partial burn off of the contact clips and carbonizing the oil.

In regard to the rupturing capacity of the oil switch in general I would like to be informed what the considerations are for giving the same switch type a higher rating on lower voltage than on higher voltage, as given by some manufacturers, catalogues. Ordinarily one would expect greater damage to the switch at lower voltage due to the greater $I^2 R$ energy in the rupturing arc. The speaker in laying out the switchboard for a 16,000-kw. hydroelectric station interconnected with others of still higher rating, suggested the use of a high generator voltage in order to lessen the possibility of trouble to oil switches under short circuit conditions but was informed by the switch manufacturer that the standard voltage of 2,300 volts would be preferable.

As the speaker at that time could not get a satisfactory explanation for this advocating a lower voltage he would appreciate very much to learn at this time the reason for this method of rating oil switches.

Dr. Steinmetz in his paper has given a very interesting exposition of the development of the present alternating current central station from the old direct current plant with particular reference to the external reactance coil as one of the characteristic protective features of the modern large sized plant. The development of this protective device was brought about by the desire to overcome the danger from the enormous short circuit current in the system, particularly in a plant with synchronous turbo-generators.

The question arises in my mind whether this heavy short circuit current could not be materially reduced by other means, possibly in addition to the proposed choke coil. The present practice of sacrificing regulation in the synchronous machines in order to reduce the short circuit current, is only a small help, and it seems that the liberal use of induction generators with their characteristic low short circuit current would aid very materially in bringing about the desired result, both as regards reduction in short circuit current as also absence of necessity for running synchronized.

This type of machinery has already been successfully installed in combination with low pressure steam turbines, and it seems that the equipment of a whole station with induction generators specially designed for a small magnetizing current in connection with synchronous motors floating idle on the system for furnishing this magnetizing current would make a feasible arrangement. The synchronous motor in such installations would have the appearance of an unproductive piece of apparatus, but for the advantage it offers by rendering the respective plant independent from any other synchronous station, its use appears justified. It might thus be considered to be in a same class with the frequency changer.

In such a system the throwing together of stations slightly out of phase may not cause nearly as heavy a shock as if both stations were equipped with synchronous machines only. The last problem stated by the author at the end of his paper, *viz.*, synchronous operation of different stations would then also find its solution.

Aside from city steam stations this induction generator type would also be of considerable advantage in a system of interconnected hydroelectric plants where it could be installed at stations of secondary importance, furnishing power only and leaving the regulation of the system to a synchronous generating station. The installation of a synchronous motor in connection with the induction generators would again render this secondary plant independent from the main station as regards regulation. Such a plant could always be run at highest efficiency, possibly without the use of hydraulic governors and could utilize the total stream flow at nearly all times without the expensive provision of a storage reservoir.

Aside from the development of the reactive coil as a protective feature of a high capacity low tension steam station there have been made developments on other protective devices serving a different purpose in stations of high voltage character, and which may perhaps properly be mentioned in discussing station development:

The aluminum arrester, although it has failed several times in the speakers experience to perform its function without being destroyed itself by mere internal disturbances in the system, represents nevertheless a considerable improvement over the older types.

In addition to the use of this arrester the speaker has advocated and put into successful operation a scheme of additional protection to station apparatus consisting in the use of solid non-coated iron wire of high permeability for station wiring, extending from the high tension transformer taps to the point where the arrester connections tap on the transmission line, which should preferably extend to the first tower outside the power house. The advantage of this scheme lies in the greatly increased ohmic resistance which the iron wire, due to the skin effect, offers to any high frequency surge such as lightning. The choke coil in particular, representing quite a length in the conductor, should be of soft Swedish iron. This scheme of using iron wire choke coils appears also to get into favor in Europe judging from a bulletin of a responsible European manufacturer of such coils recently received by the speaker.

The usual danger from high voltage building up on the reactance of the series transformer by any high frequency disturbance has been overcome by an arrangement of the speaker of shunting a small electrolytic cell across the high tension terminals of the series transformer.

Inasmuch as the skin effect of the iron wire was sought as an additional choking effect for protecting station apparatus, it had on the other hand to be removed from the path of the lightning discharge, particularly the overhead ground wire on the transmission lines was investigated by the speaker in 1909 with the result of recommending copper clad steel for ground wire purposes instead of steel which had been used exclusively before. Subsequent high frequency tests made at the University of Wisconsin on iron and copper wires have proven the speaker's arguments in favor of copper.

All the before mentioned schemes for additional protection to station apparatus have been tried out on one of the hydroelectric transmission plants built by the speaker and have worked out to entire satisfaction. This particular plant (of the Northern Hydroelectric Power Co. at High Falls, Wis.) has experienced many severe lightning storms which caused the arresters to act very frequently but there has never been the slightest damage to any of the apparatus.

A further development in lightning arresters has recently been made in Europe where a number of prominent central stations have been equipped with arresters consisting of one or more banks of condenser elements shunted by a grounding choke coil. The condenser battery acting on high frequency disturbances of any voltage, even of a very low value to which the electrolytic arrester would not respond, while the choke coil takes care of accumulated static. This arrester is reported to have given excellent results.

There are some minor details which have recently undergone development and which when taken as a whole may exert a marked beneficial influence upon the safety of central station operation.

The instrument and control panels in a large station become so numerous as to be difficult to oversee, and a reduction in their number and a clear distinction between the various instruments and panels becomes very desirable. The voltmeter and ammeter for the generators may be omitted from the respective panels and one instrument of each kind placed on a swinging bracket to serve for all the various machines by providing a receptacle and plug for each of the respective panels. A wattmeter and power factor indicator is generally sufficient for the control of the generators. If curve drawing instruments are used they may serve at same time as indicating instruments thereby rendering this latter instrument superfluous. A duplicate transmission line may be equipped with one wattmeter only by paralleling the secondaries of the respective current transformers.

The panels and the instruments should preferably be black and the instruments have their designation printed in bold types upon their scales, such as "Volts—Amperes—Watts, etc.," the graduation of the scales should be in decimals to facilitate reading. Only instruments with flat glass covers should be used to avoid the disturbing effect on the curved glass covers of the usual horizontal edgewise instruments. The illumination for the board should be accomplished by diffused light from well above the board in order to have no reflex whatever from the instruments.

The individual panels should be marked by genuine enameled name plates which do not oxidize or fade as in the case of the usual copper or paper name plate. Each circuit or group of circuits should be provided with a blue signal lamp above the board to operate in conjunction with the alarm bell in order to indicate immediately the circuit in trouble.

The above precautions may appear insignificant to the designer but they are of real value to the operator and consequently to station safety.

Besides in the Central station proper there have also been made developments in other parts of the system notably the transmission line. I wish to mention only the flexible type of transmission tower and quite recently the appearance of the composite transmission cable consisting of aluminum or copper strands and a steel center of very high elastic limit. By this arrangement the elastic limit of the composite cable is considerably increased, allowing of a wider spacing of towers with consequent reduction of cost in line construction.

D. B. Rushmore: In the President's Address this morning and in the papers which have been presented, we have the problem of disturbance from increasing magnitude—a problem most universal in the present age in social, political, industrial and engineering life. In designing for any particular condition, a design is made to meet the major point under consideration. We design machines, power plants and power transmission systems for operation, but a compromise must always be effected in considering the factors involved when we take into consideration the emergency conditions.

In the discussion that we have had on these conditions of central station operation are involved one example of a change taking place in power transmission systems, and in what are becoming very large stations for industrial power use. The magnitude of individual pieces of apparatus is increasing, the magnitude of stations, and of systems, and very largely of a number of stations tied together. While in so many of our old problems the boy, as it were, has been relatively harmless, the young man as he appears now, older, larger, stronger, and more powerful is becoming a more disturbing factor, and we have yet to look ahead to the full grown man, to the power systems that are going to cover very much larger areas than at present, and be of very much larger capacity.

In designing apparatus for these conditions a compromise is necessarily effected, and the illustration we have had of placing reactance outside of the machines, allows in many cases a better machine to be designed. While the machine has to be designed for operation, occasionally the best of machines have to be repaired, and to place a large internal reactance in machines involving high, true self-induction means, as a rule, increased difficulties in repairing machines.

To bring before the Institute one problem as yet unsolved, we have had for years in hand the development of an automatic resistance which will protect the circuit against high voltage. This has been done in the aluminum lightning arrester, which in itself essentially is an automatic resistance varying with the voltage. What we need now is an automatic reactance varying with the current, something not yet obtained, and something which is well worthy of the best study of inventors. I think that such a thing is possible, as well as likely. It has not yet been developed with sufficient rapidity to handle the problem of these large instantaneous short circuits. We must also consider that any change in condition is to be met with other changes and in connection with systems possessing large capacity or induction, all additional reactance brings with it certain possibilities which ought to demand a very much larger use of protective apparatus.

C. W. Stone: Last year at a meeting the point was raised in regard to the ultimate capacity of oil switches. In the paper by ~~Mr.~~ Cheney of Philadelphia, there was some question raised about the ultimate capacity of oil switches, and the suggestion was made that it was possible that we would need a new type of switch in order to handle these large capacities. I think the paper by Messrs. Schuchardt and Schweitzer demonstrates that by the use of reactances and the use of the larger 10 in. oil pot switches we do not need a complete redesign of the switches. The switches are large enough even to handle such systems as the Commonwealth Edison Company, and instead of being limited by the switch, it is perfectly possible to still increase the ultimate capacities of our stations.

Before I stop, there is one thing I think I should bring out, and that is I think we owe a very great debt of gratitude to the officials and engineering organization of the Commonwealth Edison Company for the very thorough way in which they have carried out these tests. There are very few places in the country where such a complete and fundamental investigation of the shocks to systems under short circuit could be made as thoroughly as they were made by the engineers of the Commonwealth Edison Company in Chicago, and I think that the whole engineering profession should feel a debt of gratitude for this paper by Messrs. Schuchardt and Schweitzer, reporting on these tests.

Mr. Merriam in his paper points out that with the 10-in. oil pot the strains or pressures are reduced to about one-third or one-fifth of what they were with the 8-in. pot. I think that is a fundamental point. One of the previous speakers mentioned the possibility of using a horizontal break. I think he lost sight of one of the fundamental principles which has been employed so generally in the type of switches described in the paper and that is by using the vertical break, it is possible to so adjust the baffles in the switch as to confine the pressures arround the arc, and thus extinguish it more readily. This is difficult to do in a horizontal break type of switch. I think if the engineers here give this matter attention, they will be convinced that the vertical break, with the type of baffling usually employed, has greater possibilities for large capacities than any other type yet proposed.

There is another point. Mr. Merriam in his paper refers to the small amount of oil which is thrown out after repeated short circuit. I think many engineers in witnessing some of these tests would have said that the amount of oil thrown out was excessive. Complete tests were made to find out how much oil could be thrown out, and the switches were opened under short circuits time after time, without changing the oil, and then the amount that had been thrown out was measured and it was found that only about five per cent had been thrown out. To be sure, it is not a dangerous amount, and yet it does demonstrate that it is advisable to install these switches in fire-proof compartments, such as brick, concrete or soapstone.

Mr. Lieb brought out the point about the possibility of the increase in the internal reactances in the generators. It is perfectly possible to design generators with higher internal reactance, but you will always sacrifice something.

I do not think that a generator with twice the internal reactance of the present machines, such as those under test, would have as big a factor of safety as the generators which are now in operation. I think also the point should be brought out that the high internal reactance generators will not accomplish what the generator with the external reactance will accomplish, and that is this—with the external reactance, in case of damage to the generator, due to the breakdown of some coil, the amount of short circuit current which can flow into the generator is limited by the reactance which is in series with it. If the generators were built for high internal reactance, and external reactance not used, the effect of the internal reactances on the generator which was damaged would be entirely eliminated, and the amount of short circuit current which could flow into that generator at that time would only be limited by the internal reactance of the other machines operating in parallel.

I think, therefore, what we should aim to do is to make the generators as safe as possible, and then protect them and the system and the oil switches by means of the external reactances.

I think another very interesting point brought out by Messrs. Schuchardt and Schweitzer is that after repeating short circuits, nearly 150 of them, there was absolutely no damage to the generators, no displacement of the coils, no displacement of the field structure or the shafting of the machine. I think that demonstrates the desirability of the reactance about as well as any point that has as yet been brought up.

B. G. Lamme: Two of the papers presented this morning have brought out the fact that reactances are advisable in the protection of large capacity alternating current generators. I fully agree with the authors of the papers on this point and have held a similar opinion for several years. Experience shows that, in commercial operation, sooner or later short circuits will occur on all generating systems, especially if they are of high voltage; and if the machines are of very large capacity the stresses exerted by the short circuit current will be so great that there must be some means provided for limiting the maximum current.

An interesting point to me in the paper by Messrs. Schuchardt and Schweitzer is the amount of reactance which they found advisable. From their tests they found that a reactance which limited the maximum current to 14 times normal was satisfactory. That is an interesting figure, for it is the one which we had reached as the limit, in our experience with large generators. We found that when we could keep the current down to 12 or 14 times normal current on dead short circuit there was very little, if any, difficulty in bracing the end windings to stand the shock. We also found that, in a great many cases, there was no difficulty in getting that amount of reactance in the machine itself without making an abnormal design.

However, that question depends somewhat on other features than on the construction of the winding itself. The speed comes in as an important condition. For instance, if you have a moderate speed turbo generator of large capacity it may require an abnormal design to obtain a high reactance inside the machine itself. If you double the speed, and thus cut the number of poles in half, you may find it difficult to obtain a low reactance in the machine. As the speed is increased and the number of poles is decreased the reactance naturally tends to increase and if the speed is made sufficiently high the machine can have sufficient reactance in itself to limit the short circuit current to a satisfactory value. That being the case, no external reactances will be required in such machines. For example, if a 10,000 to 15,000 kw., 25 cycle machine is made with two poles, 1,500 rev. per min., the internal reactance would naturally be very high. Also, if the same capacity machine for 60 cycles has four poles and operates at 1,800 revolutions, a fairly high internal reactance can readily be obtained. My experience with such machines has been that there is little or no occasion for adding reactances outside the machine.

Furthermore, in these high speed machines it does not appear to complicate the machine, or increase its cost, to obtain sufficient internal reactance. In such machines a comparatively small number of coils of large size will naturally be used and such construction tends at once toward high reactance.

One fact, which should be considered in the use of reactance, is that the higher the reactance in circuit the higher the machine will be worked for a given terminal voltage, or the lower the terminal voltage with a given generated e.m.f. In other words, the addition of reactance in the circuit directly tends to decrease the available output of the machine.

On the other hand, the conditions which tend toward increased output in the machine itself also tend toward increased internal reactance, relatively, and it may be assumed that, if the machine is constructed for high internal reactance, in many cases it can also be constructed for very high output. This interrelation of high internal reactance and high output can be illustrated in a rather simple manner. Assume, for example, that with a given number of armature slots, the ampere turns per slot can be doubled, by changing the proportions of the slots, and by various other arrangements. It is obvious that the reactance of the machine as a whole would either be increased slightly, or at least, would not be decreased. However, the output would be very materially increased and in consequence the maximum short circuit current on the machine would either be decreased or would be no greater than before, while the normal current would be increased. In consequence, the machine with increased output would have no worse short circuit conditions than before, or the conditions might even be materially improved due to increased reactance. The problem therefore turns purely upon questions of design, such as obtaining high ampere turns per slot, while at the same time avoiding excessive eddy current losses and heating in the slot conductors. Greater refinements in the proportioning of the windings are now being carried out than were thought necessary only a few years ago.

For parallelling large alternating current systems, low reactance is not a necessary condition, but relatively low resistance is required. Experience has shown that there is a certain limiting resistance which can be used, above which instability of operation will occur. The limiting value of that resistance is, to a certain extent, a function of the construction of the machines themselves. For instance, if the synchronous machines have large cage dampers on their fields, the resistance between the machines can be higher than with undamped machines. In some tests made a few years ago it was found that with an ohmic drop corresponding to 20 per cent of the terminal voltage of the machine, instability was reached with the very best damper which could be put on the field. With less damping action a lower resistance produced instability. If, therefore, a 25 per cent to 50 per cent overload condition is to be considered, then at normal load, only from 10 per cent to 12 per cent ohmic drop is permissible between the machines.

At the same time that the above tests were made for limiting resistance drop it was found that a very high reactance could be used between the machines without producing instability. The tests showed that the amount of reactance permissible was far greater than that required to limit the maximum current to a safe value in case of short circuit.

There is one point not brought out in Mr. Schuchardt's paper and that is that the damage to the winding is not merely a function of the maximum current but is also dependent upon the duration of the short circuit and also upon the number of short circuits which may occur. In connection with the New Haven Railway generators, where we had to add reactances to reduce the shocks on the machines and system, it was found that an individual short circuit apparently produced but little damage to the armature windings, but in the preliminary operation of the system, as many as 25 to 30 short circuits occurred per day, and, even with such frequent short circuits, the winding was found to stand up for months before a breakdown would occur. Also, as these machines were equipped with very heavy dampers the maximum short circuit current would hold up to practically highest value for 25 to 30 alternations, which was found to be a much more severe condition than where the short circuit was of much briefer duration. The results indicated that it was the continued hammering of the insulation by the short circuit stresses which did the most damage, and not the individual shock.

A remedy applied for this condition on these machines was the use of reactances in the circuits from the machines. These were of the iron-core type and have proven very effective. At normal load the iron is worked at such a low induction that the maximum current on short circuit will just about saturate the core. When so proportioned, an iron reactance is apparently as effective as an air-core reactance and has very little external stray field. I will say, however, that in constructing this reactance a large internal air gap is allowed—about 5 in., so that it is, to a certain extent, an air-core reactance with an iron enclosing circuit.

In these New Haven machines it was found that a reactance allowing 15 times normal current was not sufficient to protect the machines, and it was necessary to put in reactances sufficient to reduce the current to seven or eight times normal. However, the conditions were abnormal, as the output of the machines was single-phase current which required heavy cage dampers on the rotor fields in order to suppress the magnetic pulsations due to the single-phase armature reaction. With these heavy dampers the short circuit conditions were very much worse than those encountered in ordinary generators of the same capacity. Experience with other types of machines has indicated that if sufficient reactance is supplied either internally or externally, to limit the current to about 12 times normal, it will protect the usual types of machines.

W. L. Waters: The tests made at the Commonwealth Edison Co., and the system of protection there worked out, are similar to those carried out three years ago by the Westinghouse Company, in connection with the Cos Cob Power Station of the New York, New Haven and Hartford R.R. Co. At the time the single phase equipment was being installed, this power house was subjected to a continuous series of short circuits due mainly to the non-selective action of the circuit breakers; these short circuits sometimes occurring as frequently as 25 or 30 per day, and varying in intensity from a dead short circuit to one at the end of a line having 5 per cent resistance drop. The system of protection worked out for that power station was:—an improved system of armature coil bracing on the turbo generators; the connection of a 9 per cent iron cored choke coil permanently in series with the line; and series or relayed oil switches, which in cases of short circuit introduced resistance into the line, thus decreasing the magnitude of the short-circuit current and raising its power factor before finally opening the circuit. This selective circuit breaker action and somewhat elaborate system of protection was installed on account of the exceptionally severe conditions of operation, and it is probable that some less complete arrangement such as that employed by the Commonwealth Edison will afford ample protection for the average power station.

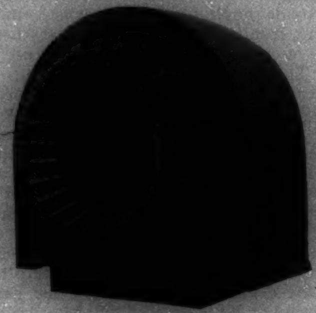

FIG. 1

The system of armature coil bracing for the turbo generators is shown in the accompanying illustration Fig. 1. It will be seen that it consists of heavy wood blocks clamping the winding to metal brackets by means of insulated bolts. This bracing can be made as rigid as desired, and has the advantage of being permanent, as it does not deteriorate with time like the rope or twine lashing sometimes used. Numerous tests have been made on generators equipped with this system of bracing, by short circuiting when excited to 30 per cent above normal voltage, and in no case has any movement of the coils been noted. In fact the shock of the short circuit seems to be felt more on the frame of the generator than on the winding.

The Westinghouse tests above referred to, which were oscillograph records made to determine the effect, on the generator short circuit current, of including various types of self induction in the circuit, were made in 1908 on 2,000 kw.; 500 kw. and 300 kw. generators, tests being made at 60 and 25 cycles, both with and without dampers on the field magnets. The majority of the tests were made single-phase as it was found impossible to obtain consistent results on three-phase tests because of variation in the time of closing for the short circuiting switches in the three phases. The results of tests checked up well with theoretical calculations; the actual shape of the short current waves being found to be dependent on the power factor of the short circuit and the phase of the current at the instant the short circuit was closed. Under the worst conditions, the current wave immediately after closing the short circuit lay entirely on one side of the zero line, and the maximum peak had a value double that figured by dividing the e.m.f. of the generator by the impedance in circuit. Under the most favorable conditions, the current wave was at all times symmetrical with regard to the zero line, and the maximum peak was approximately the same as the value obtained by dividing the e.m.f. by the generator by the impedance in circuit.

Referring to the relative advantages of auto-transformers, iron choke coils, and air choke coils, for installation in a power station to protect against lightning, surges, and short circuits, it would seem that they all have both advantages and disadvantages; provided in all cases any iron cores used are worked at a sufficiently low magnetic density, so that they do not become saturated at the maximum peak of the short circuit current. An auto transformer, if built with a sufficiently high leakage reactance will undoubtedly afford protection, but it is expensive and is a constant source of loss. A 12,000-kw., three-phase, 25-cycle 4,500 to 9,000-volt auto-transformer will have a full load efficiency of about 99.25 per cent, while the efficiency of a 12,000 kw. 9,000-volt turbo-generator is practically the same as the corresponding 4,500 volt machine, so that this 0.75 per cent loss in the transformer is not compensated for in anyway. If we assume the generator operates 50 per cent of the time and that energy costs 0.4 cent per kw-hr., this auto transformer results in an annual loss of $1,570 which capitalized at 8 per cent represents $20,000.

In regard to the relative desirability of air and iron choke coils:—an air choke coil is appreciably cheaper in first cost, but possesses the disadvantage of a strong external magnetic leakage field which is liable to effect the instruments and to produce mechanical stresses or heating in surrounding objects. It has also been found from experiment that an iron choke coil is less liable in a short circuit to produce the distorted current wave located entirely on one side of the zero line which was above referred to. So that as a result of this it would seem that an iron choke coil, provided there is no saturation at the high current values attained on short circuit, is somewhat more effective in reducing the maximum current on short circuit than would be an air choke coil having the same impedance for steady values.

John J. Frank: In the discussion of the papers by Mr. Merriam and the paper by Mr. Schuchardt and Mr. Schweitzer I will endeavor to confine my remarks to that of the designing engineer, on the current limiting reactance which forms such an important part of both papers.

Neither paper, I believe, intends to convey the impression that every distributing system great or small should be provided with a current limiting reactance as a positive insurance to the elimination of all the troubles experienced by the operating engineer.

Where the impedance of the generator and the transformers is small the introduction of a current limiting reactance will no doubt, relieve the system to a great extent of both mechanical and electrical strains. This is supported not only by the papers presented but by the experience of the Consolidated Gas & Electric Co., of Baltimore, who installed a reactance for the protection of a 5,000-kw., 13,200-volt 25-cycle turbo generator. The particular causes of excessive current are short circuits between the lines, bus bars and generator leads, and grounds on Y connected systems with grounded neutral. The possible effects in mechanical strains upon connected apparatus can best be understood by reference to the strains in a transformer.

Take for illustration a 5,000 kw., three-phase transformer, having delta connected primaries supplied with 9,000 volts, 25 cycles. The normal current in the windings is 185 amperes; the measured reactance of the windings is 2.3 per cent. With the secondary windings short-circuited and constant terminal voltage impressed upon the primary windings, the current flowing in the latter would be $\frac{185}{0.023} = 8050$ amperes. The distance between their magnetic centers is 1.7 in. = 4.32 cm.

The mechanical work of the magnetic forces of a circuit in which current is flowing is

$$W = \frac{I^2 L}{2} \qquad (1)$$

Where I is the measure of the current and L the inductance of the circuit. This quantity is analogous to the energy of a static charge, $\frac{C E^2}{2}$, and to the energy of motion, $\frac{M V^2}{2}$.

If F is the force in grams produced between primary and secondary windings, and l the distance between their magnetic centers, the mechanical work done in moving one set of coils through the distance l against the force F would be

$$W=F\times l \text{ g.-cm.} \qquad (2)$$

$$=F\times g\times l\times 10^7 \text{ joules.}$$

Hence, substituting (1) and (2)

$$Fl=\frac{I^2 L}{2 g} 10^7 \text{ g.-cm.} \qquad (3)$$

and

$$*F=\frac{i 2 L}{2 g l} 10^7 \text{ g.} \qquad (4)$$

which is the mechanical force existing between the primary and secondary windings of a transformer at the short-circuit current i.

At short-circuit, the total supply voltage e is consumed by the leakage inductance of the transformer, therefore:

$$e=2 \pi f L i \qquad (5)$$

Hence, substituting (5) in (4) gives

$$F=\frac{e i 10^7}{4 \pi f g l} \text{ g.}$$

$$=\frac{812 e i}{f l} \text{ g.} \qquad (6)$$

Inserting the values of e, i, f and l in (6) we have,

$$F=545\times 10^6 \text{ g.}$$
$$=1{,}200{,}000 \text{ lb.}$$
$$=535 \text{ tons.}$$

This force is exerted between the six faces of the three primary coils and the corresponding faces of the secondary coils; and thus on every coil there is exerted the force

$$\frac{F}{6}=89 \text{ tons.}$$

This is the average force, which varies between 0 and 178 tons, and thus reaches an enormous value.

If we denote the leakage reactance of a transformer by x, substituting $i=\frac{e}{x}$ in (6) gives as the short circuit force at maintained terminal voltage e, the value

$$F=\frac{e^2\,10^7}{4\,\pi\,f\,g\,l\,x}=\frac{f\,l\,x}{812\,e^2}\ \text{g.}$$

That is, the short circuit stresses are inversely proportional to the leakage reactance of the transformer. It follows, therefore that on systems of very large powers safety requires the use of high reactance.

In order that a reactance shall protect, its voltage characteristic should be a straight line; that is, it should be proportional to the current flowing. The following empirical formula has been followed in the design of such coils.

The voltage induced in a coil in a magnetic field is

$$E=\frac{4.44\,\phi\,f\,T}{10^8} \tag{7}$$

in which ϕ is the flux enclosed by the conductor, f the frequency in cycles per second, and T the number of turns. The flux produced by a solenoid or coil without an iron core is

$$\phi=\frac{I\,T\,d}{K} \tag{8}$$

in which I is the current in the coil, T the number of turns, d the inside diameter, and K an empirical constant which equals

$$K=0.125+0.28\frac{L}{D} \tag{8a}$$

where (see Fig. 2) L is the length and D the mean diameter of the solenoid. Substituting (8) in (7)

$$E=\frac{4.44\,I\,T^2\,d\,f}{K}\,10^8 \tag{9}$$

and

$$T=4750\,\sqrt{\frac{K\,E}{I\,d\,f}} \tag{10}$$

The latest expression of the designer is shown in the accompanying illustrations Figs. 1 and 2. The core consists of a cylinder of concrete in which are imbedded anchor plates for clamping bolts.

Radial strips of wood treated to give greatest possible insulation are attached to the core and are provided with grooves into which the conductor is wound. The conductor consists of bare stranded cable and is wound in one continuous piece as shown in the photograph so that eddy currents which might heat the solder or brazed joint in the center of the winding is eliminated. The end turns are given increased space over the average allowance to afford better reliability against electrical or magnetic shocks to which it may be subjected. In addition the conductor on the last turn at each radial support is clamped to further increase the rigidity of the coil. That the reactance operated satisfactorily in the tests made is brought out in the two papers. In order to facilitate cleaning and inspection, the cores and wooden radial supports are given a coat of cream color enamel paint. All of the bolts, nuts, and clamping members are made of brass rather than steel, to eliminate any heating due to the concentration of the flux which would be induced by a magnetic material.

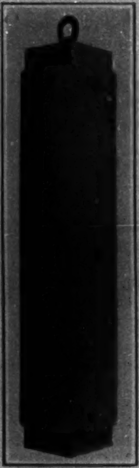

Fig. 1

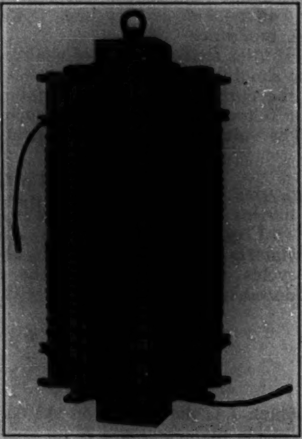

Fig. 2

Louis A. Ferguson: I would like to know whether Mr. Lamme desired to convey the impression that it would be better to use machines of high reactance rather than external reactance? My reason for asking that question is because he made the statement, if I heard him correctly, that by using machines of high reactance you could increase the output, by using a large number of coils per slot.

Our experience here in Chicago has been rather the other way; that is, we have found with our earlier large machines that there was considerable heating, and that the output for the capacity of the machine was limited, and it was necessary, in order to obtain the desired output, to reduce the number of coils per slot, and for this reason, because of the two statements going together, I would like to have him state whether in his opinion it is better to use machines of high reactance, or machines of low reactance, and external reactance connected therewith.

In replying to the question I would suggest that Mr. Lamme confine his remarks to the large machines, such as the 12,000 to 20,000-kw. and leave out of consideration the small machines of say, 1,000 to 2,000 kw.

B. G. Lamme: In machines of large capacity, such as turbogenerators, it is advisable and practicable to obtain large internal reactance by suitable design. If you can increase the number of ampere turns per slot you will tend to increase both the output and the reactance of the machine, and therefore the percentage of current on short circuit will be relatively decreased. In practice it will be found that high reactance machines are generally of relatively high output for given dimensions.

As to the matter of increasing the number of ampere turns per slot, that is a question of design principally. The difficulty with high ampere turns per slot is principally from eddy currents due to local flux conditions in the slot. Very much can be gained on this point by careful design and there is evidence that we can go much further in this regard than we have yet gone.

I think the whole tendency in turbo-generator design is toward the largest number of ampere turns which can be gotten into the armature, without increasing the dimensions, and such increase in ampere turns will also be accompanied by increase in reactance. I am in favor of putting as much reactance as possible into the machine itself up to the limiting amount required, and whenever a sufficient amount for protection cannot be put into the machine itself, then put the remainder outside. I do not favor making the internal reactance as low as possible and putting high reactances outside for I believe that this is a relatively expensive method of procedure.

R. B. Williamson: This paper has demonstrated very clearly the desirability of a certain amount of reactance in connection with large turbo-generators. This reactance may be external as in the present case, or it may be in the machine itself, provided the design is such that a high reactance winding can be used without making a less desirable design in other respects. High reactance in the generator itself means a high specific loading for the stator (*i.e.*, high value of the number of ampere-conductors per slot or per inch of periphery.) In large turbo-generators, most of the heat liberated in the stator copper must pass through the insulation and into the stator iron before it can be carried off, *i.e.*, the cooling effect of the ends of the coils is comparatively slight. In order, therefore, to limit the internal heating of the stator coils, an increase in the number of conductors per slot must be accompanied by other changes in the design, in order to limit this heating. This is particularly true in high voltage generators where the heat has to pass through a considerable thickness of insulation.

Since it is clearly desirable to have a certain amount of reactance in order to avoid the disastrous effects of short circuits on large units, and, since a high reactance involves poor inherent regulation, it follows that close inherent regulation should not be specified for such units. Moreover, it is now general practice to take care of the voltage regulation by means of automatic regulators, so that there is no great necessity for close inherent regulation.

Another point to be considered is that, other things being equal, high speed machines are more likely to be damaged by heavy short circuits than low speed ones. The internal reactance of the high speed generator will usually be less than that of the lower speed machine, but even assuming the same reactance in each case, the coils in a high speed generator span a greater angle, hence the projecting ends of coils are correspondingly longer and more difficult to support securely.

Clarence P. Fowler: In addition to the superior features mentioned, by Dr. Steinmetz, of direct current as compared with alternating current for supplying electrical energy to the congested portions of our larger cities, the following inherent advantages of the former system for this class of service, have been doubtless, in no small measure, responsible for the persistence of this system, (through the use of alternating current-direct current conversion apparatus) to the exclusion of alternating current supply:

a. With direct current available, special devices are unnecessary for charging small storage batteries, such as used in automobiles, etc.

b. As most isolated plants for office buildings, etc., are of the direct current type, the use of direct current distribution at once facilitates, the installation of breakdown service connections for such plants.

c. With alternating current distribution there is considerably more high tension feeder copper required per maximum kw. than with the alternating current-direct current system and as high tension cables cost vastly more per lb. of copper than low tension cables, it is evident that there will be quite a marked saving in this direction in favor of direct current distribution.

d. There is also quite a difference in favor of the maintenance of low-tension cables as compared with high-tension cables and even assuming equal life for each, the scrap value, at the time of removal, would be perhaps 35 per cent to 50 per cent lower for high tension than for low tension cables.

The analogy drawn between the necessity for the use of reactance in connection with our modern high voltage, high-power systems, on the one hand and the resistance of lines, feeders and mains of the older and smaller direct current systems, on the other, is interesting.

The use of reactance, as an adjunct to the operation of synchronous apparatus, as a means of affecting voltage regulation has been fully appreciated, for some time past. In 1905 the writer discussed, the possibilities of the use of reactance, for this purpose, and showed by means of waves, giving the relative phase relations of e.m.f. and current, that the inductive voltage, across a reactance, could be made additive to or subtractive from the delivered line voltage, depending upon the intensity of field charge of the connected synchronous apparatus.

It is, however, only comparatively recently that the power-limiting capabilities of reactances have come to the fore. This, no doubt, has been largely due to the marked movement toward consolidation and concentration, in the central station industry, resulting in unified systems of gigantic proportions, the loads upon which may fluctuate suddenly through a wide range or still worse, short circuits on such high-powered systems may give rise to rushes of current, the volume of which was hitherto unknown, in previous systems. The change that has taken place in the size of central stations will be apparent, when it is noted that the U. S. Department of Commerce and Labor, reports that the average size of central station grew about 72 per cent, in the five year period from 1902 to 1907.

The violent forces acting upon generating transforming and switching equipment resulting from short circuits, on high-powered systems, have, in many instances, manifested themselves in no uncertain way, in the complete destruction of the switching equipment and oftentimes with considerable damage to generating and transforming equipment, in the absence of power-limiting reactances. With the practical elimination of the reciprocating engine from these large stations and the substitution therefor of the steam turbine, a type of apparatus has been introduced the construction of which is peculiarly susceptible to mechanical strains, due to sudden surges of current of large volume. This condition in the turbine, results from the comparatively few poles employed and the consequent relatively greater throw of armature coils, and resulting lack of rigidity of the armature conducting structure. To add to the rigidity of the armature coils, various forms of coil supports, brackets, etc., have been devised, and while this method of construction has greatly aided in preventing distortion of the armature winding, it is evident the method of removing the cause of the trouble through use of properly designed reactances offers one of the most satisfactory solutions of this problem. In fact, one of the largest and most important examples of steam railroad electrification in this country, has found the use of just such reactances a most indispensable aid in the safety and reliability of its power supply apparatus.

P. Junkersfeld: The three papers presented at this session are either based upon or suggested to a large extent by the tests referred to as having been made in the plants of the Commonwealth Edison Company of Chicago. The need for making this long series of tests at considerable risk and expense was brought about by a unique situation. A very large amount of electric power supply business had been obtained and to serve this, there had been installed sixteen (16) large turbo-generators aggregating 204,000 kw. all in a little less than five years. The rapidly increasing responsibility to the consuming public of operating this unusual equipment and the large system of which it forms a part, together with the need of providing additional equipment of still greater capacity and better economy, made it absolutely necessary to make a most thorough experimental investigation and to secure the most positive information on this fundamental feature of reactance in a large system. As a result of these tests the previous tentative plan of installing 6 per cent reactance for each of the remaining thirteen (13) turbo-generators having a frequency of 25-cycles was finally approved and also the plan of installing a limited amount of reactance in each of the two tie lines connecting the Fisk and Quarry Street Stations.

I wish to express appreciation of the careful thought and much extraordinary effort on the part of all the engineers of the manufacturing and operating companies who were in any way connected with these tests, and particularly also to Dr. E. J. Berg and Dr. Chas. P. Steinmetz who gave thereto a very large amount of personal attention.

As a matter of reliability of service, the localization of the effect of breakdowns of whatever nature will probably always be the most important problem. On the one hand there is frequently the temptation to install a still larger amount of protective apparatus which may in itself occasionally cause trouble. On the other hand other methods of securing greater reliability such as independent lines or sources of supply, multiplication of lines, sectionalized operation to a greater or lesser extent, etc., may involve greater expense than is commercially justified.

Referring now to Mr. Lamme's statement, as I understand him, that repeated short circuits do more damage than individual short circuits: In our experience it is the individual short circuit on the high tension system that causes the damage, and which in most cases is so severe that the particular unit or element affected must be repaired or overhauled before it can be again put into service.

At the Annual Convention last year, the discussion of Mr. Cheyney's paper on "Oil Switches" by myself and others indicated a lack of confidence and brought out the fact that very little improvement had been made in oil switches for several years. Tests made during the past year, some of which are included in Mr. Merriam's paper, have indicated the necessity of several improvements in every type and make of oil switches that were tested. They are improvements in oil diverters and baffles, proper reinforcement of various kinds of oil vessels, effect of size of oil vessels, speed of opening, length of break, effect on oil of repeated short circuits and so on. These improvements are in a structural sense of a minor nature, but of much importance in securing more satisfactory and reliable operation of oil switches, and hence I believe we are now justified in placing more confidence in oil switches than before. There is, however, still ample room for further improvements.

It was demonstrated during the Chicago tests that it is not necessary in future that such short circuit tests be made in a large steam turbine driven power house in order to be conclusive as all of the destructive power in such short circuits was found to be due to the stored energy in the generator and none of it to the amount of steam back of the turbine. The tests and investigations described principally in the paper by Messrs. Schuchardt and Schweitzer can, therefore, now be continued in the test rooms of manufacturers as a large generator brought up to speed slowly by a comparatively small motor or prime mover will answer equally as well for further experimentation and at very much less risk and expense.

C. P. Steinmetz: In concluding I wish to say that the oil circuit breaker is one of the most common and most important pieces of apparatus, and at the same time its method of operation is least understood by most engineers, and modifications of it are still continually suggested, based on theoretical considerations, largely erroneous. We must realize that the operation of the oil circuit breaker is not based on any oil circulation, but is based on the control of the explosive forces developed at the break, for extinguishing the arc, and you can easily realize, then, that the concentric gun barrel type of switch has advantages which no other type has as yet been able to approach.

Regarding the induction generator, I have always been very much in favor of it, and I believe it is a very useful machine; and in a central station having an excessive momentary short circuit current, the addition of the induction generator reduces the percentage of short circuit current, since this machine does not add to the short circuit current. But you must realize that you could get the same effect by using generators with lower regulation. Thus, if you consider the station as a whole, there is little difference between a synchronous generator station and an induction generator station, regarding the momentary short circuit current. Every station depends in its excitation on an independent direct current excited field, in one case the synchronous alternator field, in the other case the synchronous motor field, which gives excitation to the induction generator. If you use for the excitation of the induction generator station the converters, synchronous motors, and frequency changers scattered over the system, as these are slow speed machines of low momentary short circuit current, you can materially reduce the short circuit current, but you throw the control of the system away from the generator station into the hundred or more isolated machines, all of which combine in controlling the generating station, and that is not practicable. If you have synchronous motor exciters floating on the system at the induction generator station, economy requires just as high speed machines as our present synchronous turbo-alternator, that is, machines with just as high momentary short circuit current, and you gain practically nothing; and therefore, while the induction generator is a very valuable machine in many instances, the problem of momentary short circuit current is not solved by it. The main field for the induction generator, in my mind, is in the secondary generating stations of hydroelectric systems, as it becomes possible thereby to control voltage, load and frequency of the system from a few main generating systems; the installation control and operation of the smaller induction generator stations becomes greatly simplified, and it becomes feasible to utilize smaller water powers, which could not be economically developed by synchronous machinery.

The last point I wish to bring up is the question of internal reactance as against separate reactance in the generator. That is a question which needs no further discussion, but is ancient history. The development of the generating station has long advanced beyond it. We know we must have power limiting reactance in the individual generator, and it is merely a constructive question—a question of design, whether we put it inside the alternator or outside of it, or whether we make the most economical combination possible, put into the machine as much reactance as possible without sacrificing the quality of the machine, and then put the rest of it outside of the machine.

But even if we had generators with a momentary short circuit current five or six times full load current, that would not solve the question of the operation of the present systems, because if the system is large enough, 100,000, 200,000 or 500,000 kw., you reach a limit where the operation becomes unsafe, even with power limiting generator reactances.

That is where the development has arrived, to put power limiting reactances in the bus-bars. This is really the most essential advance. In the last few years we have come to larger and larger systems, and consequently greater difficulties of operation. Apparatus which was satisfactory in a 50,000-kw. station became unsuited to the operation of a 100,000-kw. station, and apparatus which had been employed in a 100,000-kw. station will become inoperative at 500,000 kw. That was not the case in the old Edison direct current system. There, if you joined generating stations together, there was no material increase of danger, no decrease of safety, because the whole system was limited by the resistance of lines and feeders. Thus the effect of a short circuit was practically the same, whether the station was alone, or other stations were tied to it; that is, there was that feature that the danger did not increase with the increase of the system. That is the most important feature which modern development has arrived at in these alternating current systems, that by breaking up the bus-bars and tie-feeders by reactances, the danger and difficulty of operation, the strain of switches and apparatus, does not increase with any further increase of the system, and the 100,000-kw. system is just as safe or dangerous as the same system will be if extended to 500,000 or 600,000 kw. capacity. That is the great development beyond the power limitation of the generator—the use of power limiting reactances in the bus-bars, which makes an unlimited extension of the system possible without any increase of danger.

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RESPONSIBILITIES OF ELECTRICAL ENGINEERS IN MAKING APPRAISALS

BY H. M. BYLLESBY

In approaching this highly involved subject, I desire to call your attention to the wonderful achievements of our profession. Broadly, our profession is little more than thirty years old. It is true that telegraphy in its various applications and other similar branches had reached a great development at the date I consider as having been that of the birth of the electrical engineering profession in its modern sense. It is also true that the telephone at that time had come into existence as an achieved invention, but it was then purely an invention and lacking in the vast refinements and additions which have made it the huge engine of commerce and intimate feature of our modern life today. In the brief period of from thirty to thirty-four years, the profession of electrical engineering as applied to the generation, the transportation and the utilization of large quantities of electricity has come into existence.

In that brief period the wonderful achievements of electrical engineering, as just defined, have been accomplished. In the broadest sense of the term this development has required the creation of a new art. From the electrical generators of the Commonwealth Edison Company of Chicago, which are this evening furnishing the light and much of the stationary power and the bulk of the power for the movement of the intramural transportation of our great city, with a capacity of 30,000 h.p. per generator, to the generator of 30 or 34 years ago with a capacity of 50 h.p. is a far cry and a long distance.

The electrical transmission systems of thirty years ago comprised at best a few miles for supplying arc lamps and maximum distances of about a mile used in the infant industry of lighting by incandescent lamps. To-day, transmission lines of over 200 miles are not uncommon.

At the birth of our profession probably the largest steam engine did not exceed an indicated capacity of 2,000 to 2,500 h.p. and engines of that capacity were extremely rare and confined almost exclusively to slow moving pumping operations. To-day we have reciprocating engines driving electrical generators of 10,000 h.p. capacity and steam turbines driving electrical generators of 30,000 h.p. Probably these sizes will be exceeded in the not distant future. I am calling your attention to this wonderful development; this creating of a new art and the attendant collateral developments of the subsidiary machinery and materials required, for the purpose of emphasizing the points which I wish to discuss very seriously. Among other achievements, directly or indirectly, of our profession has been the great development of the water wheel. It is probable that thirty years ago there was no water wheel in existence which developed substantially more than 500 h.p. To-day water wheels are in operation developing upwards of 15,000 h.p. for the purpose of driving electrical generating machinery.

Along with the achievements of our profession and taking its inspiration therefrom, and being forced thereto by our demands, has been a contemporaneous development of machine shop practice and machine tools. To-day there is a condition of accuracy, a necessity of working to microscopic measurements and a machine shop practice which did not exist before we required it and which I believe would not have existed today excepting to fulfill our exacting needs.

Likewise the foundry of today is producing steel and iron and bronze castings in quality, in size and in accuracy—all forced upon them by the advances of the electrical engineers' profession. The entire practice of hydraulic engineering, if not revolutionized, has been thrown forward by leaps and bounds by the requirements of the electrical engineers in the useful development of water powers for the purpose of generating electricity.

Along with this has gone the scientific and painstaking study of rainfall, of runoff, of careful detail investigation of natural precipitation through rain and snow fall, the action of ice in its various forms, the action of melting snow and the control, as far as humanly possible and on a wider scale than ever dreamed of in the past, of the Titanic forces of nature in swollen streams; floods and cloudbursts. Storing water in reservoirs for the purpose of utilizing the stored or flood water at low water periods of the stream and the development of the reservoir on a scale heretofore unheard of have all been ancillary to the brains, the genius, the achievement of the men of our profession. The development of electric engineering has been a continued series of advances, step by step and leap by leap. There has been more obsolescence and more retirement of electrical machinery and tools and devices far in advance of their natural life, due to the continuing improvement, than has taken place in the history of or the development of any other art. The duties of the electrical engineer have been more eclectic, and I believe more exacting than those of any other profession.

A famous man of the world is said to have remarked during the most glorious period of the administration of the elder Pitt that "one had to look into the Gazette each morning to keep pace with the victories won." In our profession one has to read the daily press and carefully study the columns of the technical press to at all keep pace with the new developments, the new achievements and the new victories of the profession from which we all make our livelihoods. This tremendous growth from the dynamo of 50 h.p. to the generator of 30,000 h.p.; from the incandescent lamp as a luxurious curiosity to the incandescent lamp which is as much a feature of our modern civilization as our running water; from the transmission distances of a mile or two to transmission distances of 200 miles; from the electric motor existing as a laboratory toy to the electrical motor of universal use and of 10,000 to 15,000 h.p. has taken place within the span of years conventionally covered by the term a "generation." It has been achieved within the lifetime of most of the members present and it has occurred since the young manhood of many of us.

This is in truth a wonderful accomplishment. All who have contributed to it can justly take pride in the fact. It is probable the annals of civilization do not contain a parallel, but along with this proper pride, with the feeling of well merited satisfaction, let us not forget that collaterally and a part of it, something without which it could not have taken place, has been the work of the promoter and the banker. No new industry can be established, or when established can continue, and no art can grow to the dimensions of ours without the continued presence of the individual who supplies the capital, the money, the financial resource to the inventor and the engineer. Large and continuing supplies of capital are required for research, for producing inventions, for the carrying out of the inventions and the development through their period of incipiency, of temporary failures and disappointments.

It is probable that thirty-four years ago there was not to exceed $1,000,000 invested in every feature and part of this art, and today, taking the entire civilized world, and in the absence of statistics, I believe that several billions of dollars would be short of the amount of capital invested in manufacturing plants, in generating stations, distribution systems, water powers, trolley roads, motors and subsidiary details employed in the business which has been produced by electrical engineers and the promoter and capitalist working hand in hand and together during approximately a generation.

I think we should seriously consider this fact; that we should give to the promoter, to the capitalist, to the man who is able to influence capital and to place it at the disposal of the men of our profession, the credit that is properly due him. The achievement of the electrical engineer would not have been possible if it had not been for the presence of the man with money who believed in the commercial possibilities of our art as from time to time developed and who produced the capital with which to continue the development of that art. I am entirely confident, although it is a matter purely of conjecture and not susceptible of direct proof, that inventions as great as any which have revolutionized the world have died, have never been heard from because the much abused capitalist was not on hand to stand behind the inventor during his period of discouragement and disaster. I believe many other worthy inventions and developments have attracted no great notice, have not accomplished their destiny because of the absence of the man or corporation with both faith in the invention and the means of producing the capital to develop it.

Our profession has indeed been fortunate in having had associted with it from its inception men who were sufficiently intelligent, courageous and far-sighted to see the merit of the inventions and developments which from time to time were produced and who had withal the faith and the ability to continue to stand behind these inventions and developments with their capital during that period which we all know has taken place, when these inventions and these developments were under criticism, temporary failure and while only disappointing results were being reached. During this period of disappointment, of hazard, during this period of modifications from the original plans and disappointments and changes, the man or corporation with money was present to tide the infant invention or industry over the shoals and hazards which surrounded it, and except for the presence of men of the type of which I am speaking, with their courage, their faith, and their capital, many of the inventions and developments of our profession would have been in the grave of permanently disappointed hopes and non-fulfillment.

Today our art is developed. The product of the brains of the electrical engineer are so well known, their commercial utility is so thoroughly established, particularly in the principal lines of our achievements as to lead us to be forgetful perhaps of that period which the older ones of us recollect so clearly. This period, due partly to the crudity of our own devices and the undeveloped condition of our own inventions, due partly to the unstable condition of the collateral features upon which we depended such as steam engines, boilers, water wheels and manufactured articles, was a period attended with heart-breaking anxieties not only to the inventor and engineer, but do not forget that it was also a period of heart-breaking anxieties and disappointments to the man who had invested his capital in those things.

As I look back over the sweep of 30 to 34 years and from the standpoint of maturity which comes with middle age, and long experience, it is a continuing marvel to me that in spite of the perpetual disappointments and the hazards pertaining to this business, capital was found to proceed with the development of the art, and in all fairness as I look back over this period, the admiration I feel for the inventor and the engineer, the pride I take in their achievements is, in my own mind, shared with the courage and faith and enterprise of the men of capital who stood by us and our operations during those trying times.

Today there is a world of discussion regarding the value of a franchise, the terms of a franchise, the privileges it affords, the obligations it carries and the fraud which in the minds of the public is supposed always to be inseparably connected with anything bearing that name. There is much comment, nearly always unfavorable, regarding the conditions under which franchises for electric light, trolley roads and power transmission companies have been issued. If those who, probably with the best intentions possible, are criticising these matters had gone through the experience of the earlier days, they would change their opinions. In the full blaze of the glorious noon in which we now find ourselves in our profession it may be difficult but it should not be impossible, to turn our gaze backward to the early struggling days of this art, and I believe that by doing so, a more just view of the situation will result.

In those days franchises were given freely. Any one who applied for a franchise would receive it and, as a rule, without burdensome restrictions. The community which was favored by having capital build for its service an electric light plant to furnish what they believed to be a luxury and which otherwise they would not have had, or a community which was favored by a company who in return for a franchise would spend the money necessary to change the cruel and totally inadequate intramural animal transportation of that town or city to an electric transportation system was properly and deservedly welcome. The only feeling on the part of the citizens of that community or the governing body issuing that franchise was one of thankfulness that the electric light or trolley line was to be given them and one of pity for the individual or corporation who was so foolish as to invest capital in such hazardous enterprises. The same remarks apply to the development of water power. These streams were not fully developed. Some were developed for mills, but generally for usage only during the daytime and far below the capacity of the stream.

Until recently the laws governing the ownership of the power in the stream were believed to be pretty fairly understood along the lines handed down from our Anglo-Saxon ancestors. The company or individual who came into the community and produced the capital to develop these streams was royally welcome and he was viewed generally with some wonderment regarding his financial obliquity, as in the case of the individual or corporation building the electric light plant or the trolley road. If a brief and unprejudiced study is made of the history of these earlier electric light, trolley and water power companies, it will be impossible to depart from the conviction that the persistence and courage of the promoter and capitalist who carried them through their earlier periods of disaster and lack of credit is quite as notable an achievement as that of the inventors and engineers who produced the physical and scientific part of these enterprises.

This enterprise and this courage which heretofore has been wisely fostered by the commonwealth has given the United States of America the most universally extended, the best operated public utility plants in the world. In the vast majority of cases the service rendered by the corporations is furnished to the public—with superior service with its wide extensions—at less cost than in any other country. Various contributing causes have produced this result. Among these causes has been the natural inherent courage and enterprise of the American. In addition to this, however, have been the liberal franchise grants issued in the past and the freedom from onerous restrictions both for occupancy of streets and the purchase and development of water powers. A broad and liberal construction which has justified the issuance of stock which would eventually pay to the projectors and developers of these enterprises when they became successful something in addition and beyond a mere fair interest return on their investment has also had a profound influence upon giving to our country the best utility corporations of the world. Without these features this development with its low charge to the public could not have taken place. Due to these features it has taken place.

Throughout the older settled sections of our country scarcely a hamlet is without electricity for lighting and power and large sections of our farming and ranching lands are equally supplied. Due to the liberal policies in the past which allowed a reward to recompense the hazards and the courage when such hazard and courage had passed its period of financial loss, we have as a result in this country steam railroads, telegraph lines, telephone lines and gas service which in excellence of service, the extent of the service, and the price charged for such service are not equalled in the world. These broad and fair policies in the past have justified the public service corporations in extending their operations, properly expecting as a result of employing additional capital and as a compensation for the risks incurred in pledging their credit and the credit of the individuals behind these corporations, to receive an accruing profit when their enterprise and courage had been justified by results, the companies uniformly lowering from time to time the charge made for their service. No fault was found with the increasing returns upon the capital invested for the purposes and under the circumstances set forth, if at the same time the rates for service, which were already fair as compared with any other country, were being lowered.

In this way communities throughout our country are today served with public utility commodities at an actual loss to the companies serving them. These communities pay no more for the commodity of the public service corporation than the thickly settled communities, the companies operating this service having been heretofore justified in providing the capital and extending their plants into non-productive fields, standing the immediate loss resulting from this policy in consideration of an ultimate profit when their brains and energy and courage had been justified (if it was justified) by the upbuilding of these communities and the properly resulting profits then accruing. Bear in mind, as previously stated, that in the entire history of public service corporations in this country there has been heretofore a continuous lowering of the price charged for the commodity or service rendered to the public with the sole exception of the trolley roads, which started with a price to the public for service rendered which could not possibly be lowered and it is believed in many cases cannot be continued.

Abuses have taken place in the past on the part of the corporations, on the part of the public served by the corporations and on the part of the legislative and law administering bodies. At the present time my opinion is that both the public and corporation are reaching a common meeting ground, requiring public service corporations to be protected and regulated monopolies; these corporations to be governed as to their rates and to be protected from competition by so-called "public service commissions." With this doctrine as such, the public service engineer and operator has no quarrel. We do file a plea, however, that these public service commissions be composed of men of character, men of ability, men who have accomplished something in the world; that these commissions be composed of men who while fair and upright are conversant with the business which, under the laws governing their action, they are controlling.

The abuses which have undoubtedly taken place in the dealings between the municipal bodies and the public service corporations have been as distasteful to the corporations as to the public, and the cry of the corporations is for a fair hearing, for an intelligent hearing, for fair recognition of the benefits they have conferred and a demand to be relieved from the hardships and frauds which in many cases they have suffered at the hands of politicians a partially educated public sentiment and the municipal governing bodies. It is believed that properly constituted public service commissions, appointed for "good behavior," composed of high-class men, suitably paid and operating under broad and liberal laws, will accomplish this much-to-be-desired object.

Granted, as I believe it must be, that the foregoing is a candid statement of the situation, the public should recognize that the so-called public service corporations should be encouraged and fostered instead of being strangled and discouraged. The widest latitude should be afforded the operations of public service corporations under monopoly and protection, and fair laws administered by conservative and able public service commissions.

Coming now specifically to the subject of my paper, the electrical engineer must recognize that in addition to the multiplicity of duties he has been called upon to discharge, he is now confronted with a new class of responsibilities from which he cannot shrink. To these responsibilities he must give the best that is in him of experience, of fair mindedness, of wisdom and of justice. In the world at large and particularly in the United States we appear to be in the midst of a period of flux and change.

Old methods and old standards are passing away; new methods and new standards are demanded. With the marvelous progress of the civilized world since the last great economic and social changes, it will be a shame if the present crisis fails of a solution more rational and with less hardship and destruction than has attended previous solutions of economic and social crises. Out of the present controversies we must endeavor manfully and fairly to bring a condition of justice to all concerned and in our share of duty in these matters we must make every effort to be intelligent and not to be found wanting in fair dealing and honesty between man and man, between corporations and the public and between governing bodies and corporations. Principal among these new responsibilities which are being rapidly thrust upon our profession is making appraisals to determine the value of the property of a public service corporation.

These values, in accordance with the unmistakable present trend of the times, are to be made a basis upon which or from which are fixed the maximum rates which these corporations are to be allowed to charge for service rendered. There is much discussion taking place on replacement values, reproduction values, depreciation values, and intangible values. In the majority of cases the property to be appraised represents a continuing growth or a construction period from its inception. Much of the construction work we are called upon to value is concealed from view, such as foundations of buildings, foundations for machinery, submerged protions of hydraulic construction, conduit systems and gas pipes. In every case the structures or plants have been built in what is conventionally termed a "piecemeal" fashion. Almost every public service corporation has started from a small beginning and added to its plant continuously, and the finished structure today represents construction work which has been continued from the time the original property was created. In meeting the questions which the spirit of the times is demanding answers to, very properly a demand is made by all parties to the controversy that absolute and entire frankness and complete candor pervade the negotiations. Properly a period has been put to the practice of dissimulation and trickery and misrepresentation on the part of the public, the governing body, and the corporation. From a long experience I can state for my part that trickery and dissimulation and unfair dealing in the past have been fully as great on the part of the public and the governing bodies, if not greater, than on the part of the corporations. Following this proper demand for candor, I desire to call the attention of my fellow members of the American Institute of Electrical Engineers to the painful fact that it is extremely rare for a professional engineer or constructor in any branch of industry, in any branch of construction, to estimate the cost of such construction with accuracy and that the practically uniform experience has been that all such estimates have proved woefully less than the cost of the completed project.

I believe we should be candid and frank on the subject. Every one of us whose duties require him either as a principal or in an auxiliary capacity to be responsible for the furnishing of capital to build any given public service construction or to develop any given enterprise, knows full well from a long and painful experience that unless he provides for indefinite excess charges or leaves some other avenue of escape, the enterprise or construction when finished will be burdened with a floating debt which seldom is of small relative proportion. This debt is the difference between the estimated cost of building the undertaking and the actual cost as developed after the event. I believe there has not been a considerable piece of public service construction in recent years where the finished cost complete has not overrun the estimated cost by a minimum in a few cases of 10 per cent to 15 per cent to a maximum in a majority of cases of a dangerously large percentage which not infrequently has gone to an excess cost of 100 per cent. All experienced contractors will bear out the statement I have made. The comparatively few contractors who finish their career with more money than they started with, or with more money than they themselves started with and without leaving their banks or guarantee companies in the lurch have an experience of profit and loss, the loss on one job the profit on another. These men have learned their lesson and today they will only with the greatest reluctance take a contract which, under an enforceable bond, compels them to fully complete any large given piece of work for a given sum of money. Where they are forced to take any part of their contract in this manner they very properly, I think, provide for extras at a given rate, expecting that their loss on the lump work will be made up by the profit from the extras. This is too thoroughly understood to admit of any discussion.

I shall not attempt to go into detail of this well-nigh universal experience of underestimating. A large total excess cost of a completed undertaking may be represented by a small overrun in the cost of the purely physical construction and an omission of large material collateral expenditures which are part and parcel of the completed project. The shortage may be due in this view of the case to an ignorance on the part of the individual furnishing the budget to be provided; ignorance which results in overlooking a material and proper part of the cost of the completed project because it was not strictly physical construction. The overrun resulting in the floating debt therefore, in many cases, may be quite largely made up of the omission of those necessary costs which in the discussions of the times are termed "intangible values." But no matter in what direction the shortage occurs, no matter whether on the strictly physical part of the construction or from forgetfulness or ignorance of the proper costs under the head of intangible values, the facts remain substantially as I have stated in my premise.

How careful, therefore, how fair minded and liberal should be the point of view of the professional engineer in appraising the value of another man's or another corporation's property for the solemn and serious purpose of having based upon his appraisal the return which that man or that corporation is to be allowed to receive upon his investment. It is unfair that an engineer or appraiser who recognizes at the bar of his own conscience that his own estimates have been uniformly overrun should make his appraisals without taking into consideration and manfully applying to his estimate his own factor of individual inaccuracy, his own personal factor of nearly unfailing underestimating.

If the profits to be allowed public service companies were to be on a broad and liberal basis this feature would be of less importance. The spirit of the times, brought around partly by mistakes, by selfishness, by unfairness, on the part of all parties to the contract, the tendency of the times, actuated to a degree by certain irresponsible magazine writers, magazines and papers, and by certain politicians, all tend to reduce the return of the public service corporation to a low point. At best it would indicate, allowing the public service corporation after paying its operating expenses and depreciation charges, a distributable sum equivalent to from 7 per cent to a possible 10 per cent upon its reproduction value, the higher percentage being rather hoped for than indicated. It becomes plainly evident, therefore, how grievous a hardship may be worked upon corporations if the appraisal of their property is as much below the real value of their property as the average estimate of the engineer has proven in the past. I think the situation is one of the most momentous which confronts our profession today. A large part, I presume 90 per cent, of the activities of our profession have resulted from the continuing growth and existence and development of public service corporations. If these corporations through under appraisals or drastic regulations are discouraged and cease their active aggressive growth of the past it will be immediately reflected in the lessening demands made for the services of the members of our profession.

Capital is a peculiarly mobile commodity. Capital will flow from one part of the world to another in accordance with the inducements which are offered it. Capital will leave any given field with great speed if it finds that it is receiving an unfair or unjust recompense or other fields offer greater inducements. Without capital, modern enterprise is impossible. The most beneficial use of capital is to have it employed in developing new enterprises, extending existing enterprises which in turn develop and add to the wealth of the communities served. In our extending enterprises we afford profitable employment for increasing population and we ameliorate the conditions of human existence. The profession in which the members of this association are engaged could not exist at all if capital withdrew its support from enterprises depending upon the genius and ability and conscientious effort of the electrical engineer.

I urge upon all of you to carefully consider this subject, to avoid the influence of the idea that the professional engineer can get along without the services of capital. Capital on its part must treat the public, the laboring man and the professional man with fairness and liberality, with more fairness and liberality than it has in the past. On the other hand, the professional man who from the nature of his calling and its dignity carries a large influence in the community in which he operates must not forget the close co-relation between brains, labor and capital, and neither through professional indifference or professional jealousy allow himself to give capital an unfair hearing or an unjust decision.

We must avoid the fallacy that only the physical portion of a corporation's property is entitled to a value, a fallacy which has led many engineers, many business men and many corporations to disaster. The facts being that beyond the naked physical value there is required a very large and material sum to change that naked inert mass of physical construction into a live, progressive earning entity. The omission of the cost of making a going concern in addition to its naked physical value has been the root and cause, in my judgment, of a large proportion of the disasters which have overtaken enterprises in the field in which we operate.

These remarks and more to the same effect apply to the question of intangible values and when called upon to deal with these matters I hope the fullest consideration will be given to them. These intangible values generally embrace interest during construction, accidents and insurance during construction, engineering charges, supervision charges, and they should include proportionately, the tremendously large sums expended by public service corporations in developing the business, in educating the public, and producing a sale of their commodity, whose reflex effect in subsequent reduction of the operating charges should be considered as proper cost in the value of the property. Further proper charges, of an absolutely legitimate nature, to the intangible value account include the legal expenses of organization and of putting the enterprise on its feet, the discounts on securities sold or brokerage paid for finding of the capital and particularly in the case of the older companies, the large sums spent in absolute good faith in what was really a period of experimenting to obtain the best apparatus, the best systems, and methods adapted to the requirements of the company happening to be in question. Due regard should always be given to the added cost of piecemeal construction which has been an unfailing incident of all of these corporations. In all fairness it should include the losses due to obsolescence and the discarding of workable machinery long before its life had been exhausted, this discarding being for the purpose of keeping pace with the times and in the last analysis for the better serving of the public.

There is a tendency, I hope a diminishing tendency, to be unfair to public service corporations and to be entirely oblivious of the hazards and risks they have incurred in the building of their business and to be forgetful of the profound importance and great benefit they have been to the communities they serve.

A recent example and a very pertinent one of this tendency to be unfair has occurred in the appraisal of the value of one of the largest utilities in a large western city. The appraisal was for the purpose of determining the proper reproduction or replacement value of this utility. The formula was rather clearly understood as pertained to the physical property, deductions were to be made and were made for the accrued depreciation, allowances were made for what had evidently been unusually expensive piecemeal construction and matters of that description, the theory being that as regarded the physical value of this property, its appraised value would represent what it would cost to reproduce the property in its present condition.

In general this formula was carried out fairly until it was found that a material part of the distributing system of this company was now under paved streets, but that due to the enterprise or necessity of the company in the past a part of its underground system had been placed in the streets in question before they were paved; that is, the paving above this underground system on a material portion of the company's property had taken place after its distribution system was in the ground. The ruling of the body making this appraisal was that this company was not entitled as a part of its value to the cost it would have been put to of placing this distribution system under the paved streets and the difficulty of sustaining this ruling is plainly evident from the fact that wherever this company has put its distributing system underneath paved streets or where it is doing it today, the cost of that paving has applied to this company and is allowed as a part of the value of its plant. It would be hard to conceive of a more direct effort to discourage enterprise than this particular ruling. If the company had waited to put all of its distributing system under the paved streets until the paving was down and had then ripped it up and buried its distributing system it would have been allowed the cost of taking up and replacing the paving. Because it did it in advance it was not allowed that cost. This particular city is far better off from the course which that company pursued because its pavement over that particular portion of the distributing system was not injured by being taken up to put the distributing system underneath it.

We all believe we are approaching a far better understanding between all parties concerned on these questions than has existed in the past. The effort of all of us must be by conscientious effort, by candor and sincerity to bring around this better condition. However, with the tendency of the governing bodies to make decisions such as I have just referred to, how extremely important it becomes for the engineer entrusted with the making of an appraisal to be sure that he has not underestimated, to be sure that so far as his intelligence and authority go he gives to the property under consideration the benefit of all the value he believes it is entitled to, both physical and intangible.

In closing I desire to urge upon all of you a sense of the responsibilities now being thrust upon us; to urge upon you a sense of the dignity of our calling, and to express the hope that with the unusual opportunities possessed by the members of this organization for forming a basis for a proper measure of the questions of values; that we approach these subjects with high intelligence, with a profound sense of the responsibilities resting upon us and with appreciation of the fact that in the combination of capital, the public and professional engineers, no hardship can be worked to any one of the three without inevitably producing its full quota of disaster to the others.

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DEPRECIATION AS RELATED TO ELECTRICAL PROPERTIES

BY HENRY FLOY

INTRODUCTORY

There is to-day probably no subject requiring more illumination and coördination by the engineering profession than that of depreciation. The recent generally recognized necessity on the part of individuals and corporations, and the increasingly insistent demands by commissions, legislatures, and courts for proper allowances covering the reduction in worth of physical properties—be it more or less rapid—has resulted in a divergence of thought and a lack of uniformity of practice that is bewildering.

The important and wide use actually made of depreciation both in figuring operating expenses and net earnings, as well as in the determination of present values of physical properties, through appraisals, for purposes of taxation, rate making, capitalization or sale, make the subject of paramount importance to the engineer, so that the almost total absence, not alone of an approved theory of depreciation, but even the marked meagreness of authoritative literature on the subject, is striking. While certain methods have been developed and some general principles have been widely accepted, nevertheless, trustworthy engineering data on depreciation are exceedingly scarce, the application of methods of estimating depreciation varies widely and even the terms employed are used in a vague and contradictory manner.

This state of affairs exists as the result of a number of conditions, chief of which may be mentioned:

a. Confusion and non-uniformity always results from new and sudden demands to meet unforeseen and unexpectedly developed conditions.

b. The subject involves not alone the broadest engineering knowledge, but also some of the deepest economic questions, in both of which sciences but few men have had wide experience.

c. The engineers—by reason of the rapid, marvelous and revolutionary developments within recent years—have available comparatively few correlated facts and figures on which to base conclusions in order to safely prejudge the future.

d. The results obtained under different conditions of operation are so varied, the experience of different engineers on which conclusions are attempted to be based are so diversified; and finally, the training, personality and prejudice of many experts so largely qualify their opinions that unanimous conclusions have been impossible.

For whatever purpose the subject of depreciation may be considered, whether to establish reserve funds or to estimate the present value of property either in connection with " original costs " or " cost to reproduce new ", it is essential that the work of the engineer stand the scrutiny of the courts, so that frequent reference herein will be made to judicial rulings. While many court decisions seem more or less contradictory and the Supreme Court has not squarely passed on proper methods for estimating depreciation many recent decisions are enlightening, in determining a theory of depreciation.

The courts repeatedly use " fair value " as the only one which should be recognized and it is this value that the engineer must bear in mind when estimating depreciation. As shown hereafter under "Going Value," fair value includes something in addition to physical values in which the engineer is primarily interested. But what is the " fair value " of the physical property?

It must be admitted that where engineers of experience, good judgment and integrity, appointed even by opposite " sides " may be expected to approximately agree on the " original cost " or the " cost to reproduce new " they differ much more widely in attempting to determine depreciation. This in part arises from honest differences of opinion, as the problems are not possible of exact mathematical solution and the gradations from one class of depreciation to another are frequently so gradual as to be barely distinguishable. Moreover, there is much, evidently sincere but nevertheless mistaken, opposition to the application of any principle of depreciation in determining the value of going properties; and yet, a consideration of what depreciation—if any—has taken place in the physical property of every corporation must be had, in order to obtain a safe—though it may be very approximate—indication as to proper or improper capitalization.

Some authorities hold that it makes no difference, and the engineer is not interested in the purpose for which the values determined by him are to be used; that in engineering work, facts and figures, modified as little as practicable by personal opinion, are alone to be taken into account, and that the answer is to be the same whether the results are to be used as a basis for making rates, or assessing taxes, or realization from a sale, or the issuance of securities. While this position may be correct with reference to ascertaining "original costs" or "cost to reproduce new", it certainly does not apply when depreciation is considered because there are different classes of depreciation and the term is used to mean several different things, as shown more fully below and under the paragraph "Absolute and Theoretical Depreciation"; hence, the expert *should know for what purpose his depreciation figures are to be used.*

No attempt will be made in this paper to determine the appropriate relation of physical to intangible or capitalization values; nor will it consider, in the application of methods of depreciation, whether "original cost" or "cost to reproduce new" is the proper basis for determining the present value of the physical property.

APPLICATION OF TERMS

Depreciation, like perpetual motion, implies constant action; but only in this are they alike, for as the practitioner knows, depreciation is an inexorable reality while perpetual motion is but an alluring chimera. Webster defines "Depreciation" as the "act or state of lessening the worth of", and in this sense it will be used by the writer regardless of the source or method of worth reduction, or by what means it may or may not be removed. The term "amortization" has been used somewhat indiscriminately for depreciation, but it should properly be applied only to the laying aside of funds at a uniform rate for the ultimate replacement of capital investment; and in this sense alone will be used by the author.

Depreciation has been used to mean:

1. The annual amount expressed, as a percentage or in dollars, that should be laid aside to renew or replace the article in question

at the time of its abandonment. In this use of the term, the loss of worth, which can be made good or replaced through ordinary maintenance or repairs, is not included as a part of depreciation, but is provided as a part of the regular operating expenses. This, until comparatively recently, was the more common use of the term depreciation which was applied particularly to renewals and replacements. Used in this sense, the term " depreciation " is somewhat academic and theoretical, and may or may not represent any actual financial outlay.

> " Depreciation does not represent actual expenditure but the amount properly reserved to offset the loss in value occurring to the operating plant."*

2. The annual amount expressed, as a percentage or in dollars, that should be laid aside to renew or replace the article in question at the time of its abandonment, plus the annual expense of maintenance and repair expended in removing such part of depreciation as is practicable and good economy. This then includes all classes of " lessening of worth " and is the application of the term preferred by the writer and used by the New York Public Service Commissions in their rules for uniform accounting:

> " The next important step to be taken by the corporation is to determine what amount should be set aside month by month to cover wear and tear, obsolescence and inadequacy—repairs, renewals, replacements and other depreciation."†

3. The total amount—it may be the sum of several years of depreciation—expressed in a percentage or in dollars, that must be deducted from the " original cost " plus appreciation or the " cost to reproduce new " in order to obtain the present value. The determination of the amount of depreciation at a given time, in connection with the valuation of a property, is merely the summation of the annual accrued amounts of deterioration, which, from the time of installation, have been continuously reducing the worth of the property, less such value as has been restored by expenditures for wear and tear, replacements and renewals.

Physical Value. This expression is usually recognized to represent those elements of cost incurred in installing and putting the physical property in a condition to begin operation. It includes primarily, " those things which are visible and tangible,

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*Cunningham *vs.* Chippewa Falls Water Works and Lighting Company, Railroad Commission of Wisconsin.

†Report of the Commission adopted December 8, 1908, in the matter of " Uniform Systems of Accounts for Public Service Corporations."

capable of being inventoried;"† but secondarily, certain non-physical charges " which are an inseparable part of the cost of construction but which do not appear in the inventory of the completed property."† These secondary values which are to be included as a part of the physical property are expenditures for such items as:

1. Engineers' and architects' fees, including cost of design and testing all construction and equipment, etc.

2. Administration expenses chargeable to construction, including superintendence, inspection, accounting, salaries of officers and clerks, consents of authorities and property owners for temporary work or use, legal expenses, rent, printing, storeroom expenses, etc.

3. Provision for various incidentals and contingencies, incomplete inventories, unforeseen requirements, etc., which practical experience has shown to be necessary.

Development Expenses, Intangible or Overhead Values. Any one of these terms is generally used to include certain expenses, which, while a necessary part of the complete cost of a going property, are not costs inherently a part of the construction of the physical property, as such.

Development expenses generally cover most or all of the following expenditures:

1. Legal and other expenses of preliminary promotion, incorporation and organization, procuring consents of property owners, condemnation proceedings, obtaining franchises, consents and certificates from Public Service Commissions and other public bodies, title examinations and insurance.

2. Technical expenses in connection with preliminary work, surveys, expert estimates, etc.

3. Interest on capital and bond issues, wages of superintendence and administration not chargeable to construction ordinarily necessary in connection with putting a property in going order; and also sometimes the deficiency in operating expenses and fair return until the property is put on a paying basis.

4. Taxes of various amounts including corporation tax, mortgage tax, real estate tax, personal property tax, capital and State tax, franchise tax, etc., which must be provided and paid until the property is completely a " going concern ".

5. Discounts on securities, brokerage or other customary and

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†" Valuation of Public Service Corporations Property ", by H. E. Riggs, Proceedings American Society of Civil Engineers, November, 1910.

necessary expenditures in connection with financing such an undertaking and marketing securities.

6. Reasonable promotion profit, possibly also compensation for risk of capital, estimated at 5 to 10 per cent of the cash investment.

Development expenses are not ordinarily depreciated in the same way as the physical property, though some authorities have indicated such procedure is proper. Development expenses may well be amortized, but the rate of such amortization has no necessary connection with the rate of depreciation of the physical property. The rate of amortization of development expenses might well be based on the life of the securities, for example, 50 years, whereas the depreciation of the physical property would have to be based on its rate of deterioration through life, which the Wisconsin Commission reports to average for electric lighting properties, 17.46 years, telephone plants 11.24 years, and electric railways, 18.02 years.

Original Cost. As the term indicates, this refers to the actual amount of money paid for the physical property including original construction plus all additions since that time. Original cost should be shown in the books of corporations, but is not always there obtainable. In making deduction for depreciation all authorities agree that the value of any property that has been abandoned or discarded should be entirely written off, unless possibly the earnings have been so small as to preclude doing so at once without unfairness to the stockholders or bankruptcy to the corporation.

Cost to Reproduce New, or Cost of Reproduction. These terms, so much in evidence nowadays, refer to an estimated value based on the cost of reproducing the physical property new, on the basis of prices current at the time of estimate—prices that fluctuate considerably are averaged for five years preceding—and is made up to include everything that can be inventoried regardless of original cost, age, service value or present condition as effected by depreciation.

Scrap Value. All physical property unless offset in whole or in part by cost of removal, has a certain scrap or junk value beyond which there is no depreciation, hence physical property can only deteriorate until it reaches its scrap value. This value is simply the fair market price that a purchaser will pay for the property in its disintegrated condition. If a property consisting of its several elements is usable not as junk but as serviceable property elsewhere, a higher price than scrap value is obtainable, and this worth has been characterized as "salvage value" or "minimum going value."

Wearing Value. If from the cost—taken on whatever basis is determined to be the correct one—there is subtracted "scrap" or "salvage" value of given physical property, the remainder is a value known as "wearing value," which will deteriorate more or less rapidly and entirely pass away, as regards the installation being considered, at the expired life of said property, which life ceases through age, inadequacy, obsolescence or sudden damage.

Service Value. Physical property, honestly and intelligently purchased with a view to its suitableness for the service intended, aside from some hidden defect or untoward accident; maintains its original value practically throughout its life except for such deterioration as results from wear and tear possibly, or deferred maintenance. The life of the property may expire normally through age or prematurely through inadequacy or obsolescence but these two latter classes of depreciation develop quickly so that for the larger part of the time used, the service value of property will approximate original cost. Service value must not be confounded with going value. Service value results from the use of the property in the place and for the purpose for which it was intended. Going value may or may not accrue in addition to, and, over-and-above service value. Going value relates to establishment of earnings while service value exists regardless of earnings.

Present Value. This expression refers to the estimated worth of the physical property as it exists at the period being considered. It may have one of several values, some purely academic and artificial as explained more fully hereafter, depending on what application is made of the theory of depreciation and therefore, present value always needs some qualification or explanation as to the sense in which the term is used. The more frequent application of the term is to that value obtained by deducting from "original cost" plus appreciation or "cost to reproduce new," the accrued depreciation, which may be either absolute depreciation or the sum of both absolute and theoretical depreciation. Though usually so, "present value" does not necessarily include a deduction from cost to cover deterioration as is illustrated in the valuation of the Texas Railroads made by the Commission of that State, where no deduction from cost of reproduction was made on account of existing wear and tear or normal deterioration.

Appreciation as well as depreciation must be considered in determining "present vlaue" as indicated by the Supreme Court.

> "And we concur with the court below in holding that the value of the property is to be determined as of the time when the inquiry is made regarding the rates. If the property, which legally enters into the consideration of the question of rates, has increased in value since it was acquired, the company is entitled to the benefit of such increase." *

"Original cost" or "cost of reproduction new," in connection with depreciation of the physical property inventoried is quite generally used in determining present value, but in this connection it is interesting to note the unique opinion of the Iowa Supreme Court, which in view of the numerous decisions of other courts can hardly be considered a safe precedent to follow:

> "The contention illustrated how inequitable would be a rule arbitrarily fixing the value as that for which a system might be replaced. Aside from this being impractical it may safely be said that there is hardly an enterprise of this character which, were it destroyed, would be restored as it was before. In ascertaining values in this way, the worth of a new plant of equal capacity, efficiency and durability, with proper discounts for defects in the old and depreciation for use, should be the measure of value rather than the cost of exact duplication."†

In estimating "present value" it is perhaps unnecessary to state that "second hand", "scrap" or "forced sale" values are not the "fair values" to be considered in connection with a "going concern." This has been repeatedly affirmed by the courts, as indicated, for example, by the following decision from the Supreme Court of Maine.

> "Now what is the property which the district has taken by power of eminent domain? In the first place it is a structure, pure and simple, consisting of pipes, pumps, engines, land rights, and water rights. As a structure, it has value independent of any use, or right to use, where it is, a value probably much less than it cost, unless it can be used where it is, that is, there is a right to use it. Nevertheless, it has value as a structure. But, more than this, it is a structure in actual use, a use remunerative to some extent. It has customers, it is actually engaged in business, it is a going concern. The value of the structure is enhanced by the fact that it is used in, and in fact is essential to, a going concern business. We speak sometimes of a going concern value as it is, or could be, separate

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*Wilcox *vs.* Consolidated Gas Company, 212 U. S. Page 52.

†Cedar Rapids Gas Light Company *vs.* City of Cedar Rapids, 120 N. W., 966.

and distinct from structure value—so much for structure and so much for going concern. But this is not an accurate statement. The going concern part of it has no existence except as a characteristic of the structure. If no structure, no going concern. If a structure in use, it is a structure whose value is affected by the fact that it is in use. There is only one value. It is the value of the structure as being used. That is all there is of it."*

In obtaining the depreciated value of "used or useful" property, worn out or replaced inventoried material which has no value except for sale, may be put in at scrap or salvage value, unless such property is being carried merely to artificially increase values.

Going Value. This refers to an estimated worth recognized by the highest courts and ingeniously figured and allowed for by at least one State Commission in connection with a wise expenditure made in increasing the business of an established plant.

Judge Lurton in the decision of the Supreme Court in the Omaha Water Works' case, decided May 31, 1910, says:†

> "The option to purchase excluded any value on account of unexpired franchise, but it did not limit the value to the bare bones of the plant, its physical properties, such as its lands, its machinery, its water-pipes or settling reservoirs, nor to what it would take to reproduce each of its physical features. The value, in equity and justice, must include whatever is contributed by the fact of the connection of the items making a complete and operating plant.
>
> "The difference between a dead plant and a live one is a real value, and is independent of any franchise to go on, or any mere good will as between such a plant and its customers. That kind of good will as suggested in Wilcox *vs.* Consolidated Gas Company (212 U. S., 19), is of little or no commercial value when the business is, as here, a natural monopoly, with which the customer must deal, whether he will or not. That there is a difference between even the cost of duplication, less depreciation, of the elements making up the water company plant and the commercial value of the business as a going concern is evident. Such an allowance was upheld in National Water Works Company *vs.* Kansas City (62 Fed., 853) where the opinion was by Mr. Justice Brewer. We can add nothing to the reasoning of the learned Justice, and shall not try to. That case has been approved and followed in Gloucester Water Supply Company *vs.* Gloucester (179 Mass., 365, and 60 N. E., 977) and Norwich Gas and Electric Company *vs.* Norwich (76 Conn., 565). No such question was considered in Knoxville Water Company (212 U. S., 1) or in Wilcox *vs.* Consolidated Gas Company (212 U. S., 19). Both cases were rate cases and did not concern the ascertainment of value under contracts of sale."

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*99 Maine, 371.

†Omaha *v.* Omaha Water Co., 218 U. S., 180.

The above decision of the court would imply that a different valuation should be allowed and recognized in determining rate cases, for example, as against valuations for purposes of sale. The writer can conceive of no equitable reason for such distinction aside from some contract stipulation. No investor wants to take title at one price and then find that his earnings are to be fixed on another and depreciated basis. Worth for rate-making purposes, is the only worth that the investor will consider if his earnings are to be regulated.

Good Will. A monopoly, as is generally admitted, has no good will which can be evaluated, and the courts have sustained this view. Good will can only result where competition exists and the tendency of the times is to make no allowance for this element in a public utility valuation; it being considered that good will belongs rather to industrial enterprises where its value is determined by the profitableness of the business; namely, capitalizing the net income. Good will has no value which must be considered in dealing with the subject of Depreciation.

Franchises. As the term indicates, it is the right to "do business". Formerly franchises were considered more or less valuable assets and in some instances, have been recognized and allowed for by the courts; but the present tendency, largely by reason of legislative enactments, is to prohibit the capitalization of franchises beyond the absolute expenditures made in good faith in obtaining said franchises. Depreciation of franchises depends on their terms and has no relation to deterioration of the physical property although the expiration of a franchise might easily reduce service value.

CLASSES OF DEPRECIATION

The subject of Depreciation from an engineering—not an accountant's standpoint—practically divides itself into several classes, as follows:

Wear and Tear, or Maintenance. This includes such depreciation as may ordinarily be removed or offset by proper expenditures at such time as the worn out parts may be economically replaced. Few parts of physical property in use ever become completely worn out; after a certain amount of wear, a point is reached at which good engineering requires their replacement; they may be still further used, but only at the cost of economy or safety. With different pieces of apparatus, depreciation due to wear and tear varies widely. It may amount to a small percentage of the whole, as for example, the bearings in a generator; or it may amount to a very large percentage, as for example the blading of a steam turbine or the insulation of a high-tension leaded cable. This class of depreciation may be considered to include that due to accidents, such as would result from lightning, fire, or other sudden damage.

Even before the moment original construction is complete, deterioration begins and a more or less depreciated condition of the installation as a whole always exists, which condition will increase until good engineering indicates that the time has come to offset wear and tear by repair. Such depreciation, as related to service value, not always as to sales value, can usually be completely compensated for by expenditures small, relative to the value of the entire property. It has been the almost universal custom to include the expense of removing wear and tear, the most obvious class of depreciation, as part of regular operating expense.

Age or Decrepitude. Depreciation of this sort is due to the ageing of apparatus that usually has a life extending over a period of years. Property that is short-lived, usually passes away through "wear and tear." In many instances, age depreciation will be the same whether the apparatus is used or unused; *i.e.*, a boiler or an insulated wire will deteriorate through the action of the elements practically as rapidly when standing idle as when in continual service. After a given number of years, the expense of maintenance on very many pieces of property will become so large that it is more economical to abandon than replace it. For example, car bodies will in the course of time, become so racked that they must be abandoned because the new cost less than repairing the old.

Inadequacy or Supersession. This class of depreciation arises from increased demands of service so as to render the property in use inconvenient or uneconomical for continuance of operation, although in every way capable of performing the service for which it was installed. For example, when street railway service has increased to such an extent that many and frequent small single-truck cars are required to do the work that can be done by larger double-truck cars at less cost and with less interference with street traffic, both economy and necessity compel superseding the smaller equipment by the larger, and thus through inadequacy, investment in the smaller equipment is depreciated before the property is worn out or becomes decrepit. Furthermore, the introduction of heavier cars may make inadequate the rails and car barns. Inadequacy may and does take place without regard to the length of time the property has been in use or to the amount of service rendered. Inadequacy, although confused by some authorities with obsolescence, is generally distinct from the latter and usually arises from a different cause, although in some cases related to and scarcely distinguishable from obsolescence.

Obsolescence. Obsolescence means the depreciation of property through the development of something newer and either more economical or more of a fad. Like inadequacy, it may necessitate the abandonment of property long before it is worn out and in many cases, arises largely from demands of the public. What is obsolete in one place may not be effected by obsolescence in another. Note for example, the recent introduction of P. A. Y. E. cars in the larger cities or the use of open-bench cars in the Borough of Bronx, where they are considered good practice while at the same time they are considered obsolete for the Borough of Manhattan, all within New York City. The substitution of underground conduits and cables for aerial construction required by public authorities is another illustration of this class of depreciation which cannot be prevented by maintenance or offset by repairs; it can only be met by complete replacement. By reason of rapid advance and development in the art, obsolescence has heretofore probably caused the greatest expenditure for depreciation account, unless it is wear and tear; but as time goes on, obsolescence may become a less important factor, though it would probably be at the cost of improvements and development.

> "There is also the question of obsolescence, or such changes as become necessary because of new inventions or because of changes in the art. In the electrical field in particular, such changes are very frequent. They often make it necessary to discard machinery and other equipment of various kinds long before they are worn out. This is an expense that is of the same nature as depreciation and is usually classed as such. It should be charged to operating expenses the same as other depreciation."*

Deferred Maintenance. The several classes of depreciation hereinbefore referred to assume that the property will be kept in good operating condition and efficiency. If the condition of

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*Decision of the Railroad Commission of Wisconsin, June 2, 1908, City of Dodgeville *vs.* Dodgeville Electric Light and Power Company.

the property is permitted to lapse beyond that of safety or economy in operation there results a condition due to neglect of proper maintenance and regular repairs, a condition known as "Deferred Maintenance," which is measured by the expenditure that may be necessary to offset such neglect and restore the property to good operating condition. Deferred maintenance is only another term for neglect and always reflects to the discredit of the management or the financial ability of a corporation.

"Absolute" and "Theoretical" Depreciation

Before undertaking to discuss proper methods of estimating and allowing for depreciation, it is essential to have clearly in mind just how depreciation actually takes place and in what way it effects physical property.

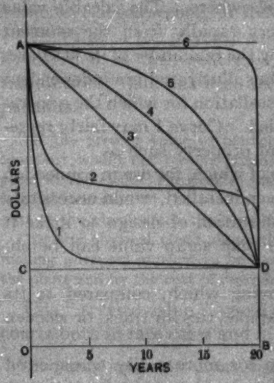

Fig. 1

Where property is no longer of service, it must be depreciated down to the value at which it may be sold, even though that value is as low as scrap value. On the other hand, apparatus that is in use and rendering a service economically, may for the purpose for which it was intended, be as valuable as when originally installed, although its age may be approaching the limit of its life. Take for example, a steam engine which though having been in use the greater part of its estimated life is, through proper maintenance, in as good a condition to render service as at any time in its history. If its annual maintenance charge is no greater than in the earlier years of its history, its "service value" to the company as a going piece of property is as great as when first installed. What then do we mean by depreciation? Reference to Fig. 1, indicates graphically several ways in which depreciation actually takes place, as well as usual methods heretofore adopted in considering and evaluating depreciation.

Assume that a given piece of physical property has an estimated life of twenty years, represented by the abscissa *O B*, and that it has a given value in dollars, shown by the length of the ordinate *O A*. Let the ordinate *O C* represent the worth in dollars of the apparatus as scrap or junk, then the abscissa *C D* will represent the scrap value throughout the life. This line is always approximately a straight line, deviating therefrom simply by fluctuations in the value of scrap material, which is usually within fairly narrow limits. The point *D* is the value of the apparatus in question at the end of its life. It may reach this value through any one of several methods of depreciation, shown graphically by the curves No. 1, 2, 3, 4, 5 and 6.

Curves 1, 2 and 6 may be said to represent " absolute depreciation "; and curves 3, 4 and 5 " theoretical depreciation." Curves 1 and 2 represent the values, during any period of their lives of most pieces of physical property, determined from the standpoint of bargain and sale for use elsewhere. The saleable value of new apparatus depreciates very rapidly from the moment installed and then gradually during the remainder of its life down to " scrap value." The values thus illustrated are independent of the service for the particular installation for which the apparatus has been purchased and installed. Curve 1 may fairly represent the worth of certain pieces of property such as

a. Special machinery, the value of which, for use in connection other than that for which it has been installed, would necessitate such a large expenditure for modification of design to make it useful elsewhere, that little more than scrap value can be obtained for same.

b. Property, the cost of removing which, compared to its cost new, is relatively high; for example, ties for track, or wooden poles of a transmission line.

Curve 2 represents sales value for more easily transported property, as for example, the rolling stock equipment of a street railway system.

The classes of depreciation indicated by the curves 1 and 2, might properly be called salvage values and approximate scrap or junk values, the principal difference being the property is sold for what it is worth as a unit rather than for its dismembered elements. It will be evident at once that depreciation of these classes cannot fairly be used in determining the value of physical property of an operating entity. That this is true and the view taken by the courts, will be evident from consideration of the decisions in the Consolidated Gas and other similar cases and even in the Knoxville Water case, which is generally considered the most radical decision in the way of depreciating physical value.

Curve 6 indicates only depreciation due to wear and tear until just before the close of life, at which time other classes of deterioration may appear. The curve is based on the assumption that the apparatus in question will be used in connection with the purpose for which it was installed throughout its life, and being maintained in good operating efficiency, 100 per cent, is just as good for the purpose of use, as the day it was installed, although there may be slight deterioration resulting from wear and tear. The worth represented by this curve, 6, may be called the "service value," and it is the real value of its physical property to a "going concern." Most classes of apparatus or property of a going organization follow this curve 6, unless effected by inadequacy, obsolescence, or deferred maintenance.

The value of the physical property, as indicated, for example, by curve 6, is that generally allowed in "purchase and sale transactions," and has been recognized by Public Service Commissions.

> "If the present value exclusively were to be taken as the basis, respondent would not receive credit for having installed any part of its plant at full cost. The present value, as of June 30, 1908, must, therefore, be increased by the amount of the estimated depreciation on that part of the plant which the company installed new."*
>
> "Of the physical plant alone, the most equitable valuation for rate-making purposes appears to be best represented by the original cost of the plant and by the cost of reproducing it."†

This "service value" would also seem to be recognized by the courts both in rate cases and in determining valuations for sale.‡

> "Probably a fair statement would be that the physical value of the plant is its value as a performing plant for the purposes for which it was designed."§

If any contrary position were assumed, namely, that only "sales value," indicated by curves 1 and 2, were to be used in determining present value, then a large portion of every going

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*F. B. L. Fullmer *vs.* Wausau Street Railroad Co., Railroad Commission of Wisconsin, April 1, 1910.

†G. W. Hill et al., *vs.* Antigo Water Company, Railroad Commission of Wisconsin, August 3, 1909.

‡City of Omaha *vs.* Omaha Water Co., 218 U. S. decided May 31, 1910. Wilcox *vs.* Consolidated Gas Co., 212 U. S., 19.

§Columbus Railway & Light Co. *vs.* City of Columbus, Circuit Court U. S. Southern District of Ohio, report of Master, page 34.

property would be valueless, because the expense of removal would amount to more than the cost of new in the open market; for example, ties in a railway property; foundations and settings for machinery; pipe, deeply buried; cross-arms and many wooden poles.

The classes of depreciation above discussed are going on constantly in any physical installation. They are at work and in evidence at any time despite the honest effort and even extravagant expenditure of the management to provide against and forestall depreciation. Property—except real estate or road bed—cannot be maintained at 100 per cent of its original value and ultimate economy seeks only 100 per cent operating efficiency. The complete physical plant of a going property would not have a higher service value than 90 or 95 per cent and the realizable sales value might be as low as 20 or 30 per cent.

In contradistinction to determination of present value by the use of depreciation expressed in the curves 1, 2 and 6, which may be termed "absolute", the curves 3, 4 and 5 indicate several classes of "theoretical" depreciation, which have been quite widely used in some cases for estimating present values, but more often for determining the yearly theoretical deterioration for purposes of establishing depreciation funds, which is quite a different subject.

The erroneous application of rates of depreciation in the attempt to determine present commercial values, is fairly common. One of the most notable cases, because of the large amounts of money involved, being that of the public Service Commission of New York, First District, in the matter of the Third Avenue Railroad Reorganization.*

These three curves 3, 4 and 5 represent classes of depreciation which seldom, if ever, occur in practice; but are convenient for purposes of estimate, particularly curve 3, which represents what is called "straight line depreciation". As indicated, it assumes a gradual and constant reduction in the value of property throughout its life. The significance is that if, from the cost of apparatus, the value to be obtained at the end of its life, namely, the scrap value, is deducted, the remainder divided by the assumed life of the apparatus will give the amount in dollars to be laid aside annually to accumulate a fund sufficient to replace the property at the end of its life, without interest.

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*Opinion of Public Service Commission for the First District, New York, Disapproving Plan of Reorganization, July 29, 1910.

Curve 4 is closely related to curve 3; the annual depreciation fund, however, being less because it is assumed that the uniform amount of money laid aside annually during the life of the property will be put out at interest and compounded, so that owing to the accumulation of interest the amounts annually laid aside will be less than in the case of " straight depreciation ". Curve 4 is called the " sinking fund " method.

Curve 5, a modification of curve 4, is based on the assumption that instead of laying aside a regular amount annually and compounding, the amount laid aside will be small at first gradually increasing in amount as the earning power of a property increases, as it generally does, with its life. These amounts are then assumed to be put out at compound interest so as to aggregate original cost of the apparatus at the end of its life. No general rule has been developed as to the proper amounts to begin laying aside or in what proportion they shall increase; but it is clear that the smaller are the amounts in the beginning the larger they must be toward the end of the life of the apparatus.

This latter plan of providing depreciation funds has the advantage of more nearly proportioning the annual depreciation payments in accordance with revenue, and for most pieces of property will more clearly approximate the deterioration actually taking place.

A fourth plan of determining " theoretical " depreciation, has been used to a limited extent. It consists in assuming a given life for the property in question, ascertaining the annual rate of depreciation and then applying that rate uniformly to the principal diminished in amount each year by the deduction for deterioration. For example, if the principal invested were $2,000 and the rate assumed is 10 per cent, the amount charged off for depreciation the first year would be $200, leaving the principal, $1,800 on which 10 per cent or $180 would be charged off the second year, and $162 the third year, *et cetera*; thus the amount charged off becomes progressively less and the life of the property becomes theoretically at least, infinite. Of course, this method can be modified from the " straight line " depreciation illustration used above to the " sinking fund " method, if desired.

From the above it will be seen that any one of these four methods of estimating depreciation is based on absolutely arbitrary assumptions. Practically there is no more logical reason per se why we should provide the fund necessary to replace the property at the end of its life in any one of the several methods suggested by the curves rather than in any other of the several methods. Each method will accomplish the same result but it will be seen at a glance that in applying curves 3, 4 or 5, the amounts to be laid aside annually will vary considerably, and to that extent effect net income; similarly, the effect on the worth of the owner's investment will also vary with the curve used, being appreciably less for "straight line" depreciation. Where the lives of property considered are relatively short, the result of using any one of these three curves is less pronounced; but where the lives are long, running to 50 or 100 years, the difference for the major portion of their lives is marked. The fourth plan suggested has not the advantage of being sound theoretically or advantageous practically.

The "straight line" method of depreciation has been more largely used than any other probably because the lives of much apparatus is brief; and furthermore, the application of this method is the most simple, direct and easily understood, and hence favored by the legal fraternity, and a large proportion of the members of public utility commissions, many of whom, not technical men, naturally incline toward the more easily appreciated elements of the questions which they are compelled to consider and discuss.

There are three other methods of determining the depreciated value, that is the present value, of physical property which should be mentioned.

The first consists in estimating the cost of purchasing and installing second-hand or used, apparatus, of the type and character of that installed and equivalent for the same work. The difficulty of carrying out this method in practice is the impracticability of finding duplicate, used apparatus and obtaining fair or uniform standards of price thereon.

The second: some authorities claim that the depreciated value of a plant should be determined by comparison with the cost of a most modern installation designed to do the same work. This method has apparently received some encouragement from the courts, as indicated by the quotation from the decision in the Cedar Rapids case, referred to under "Present Value."

A third method of ascertaining present value is to make an estimate of the cost of reproducing the physical property new and deducting therefrom the estimated expense of putting the existing property in a condition equal to new. None of the three methods just mentioned above, are generally favored.

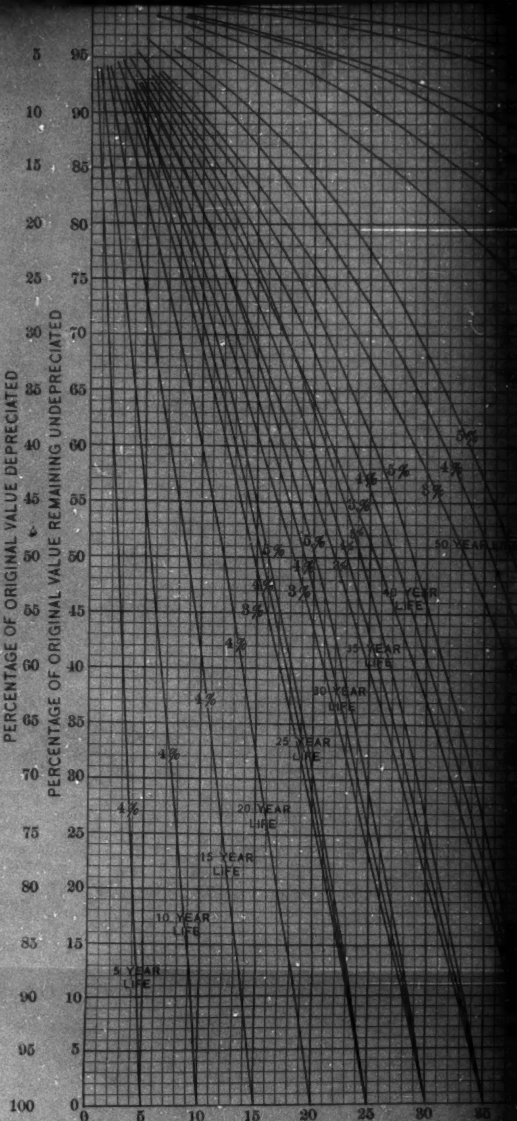
PERCENTAGE OF ORIGINAL VALUE DEPRECIATED
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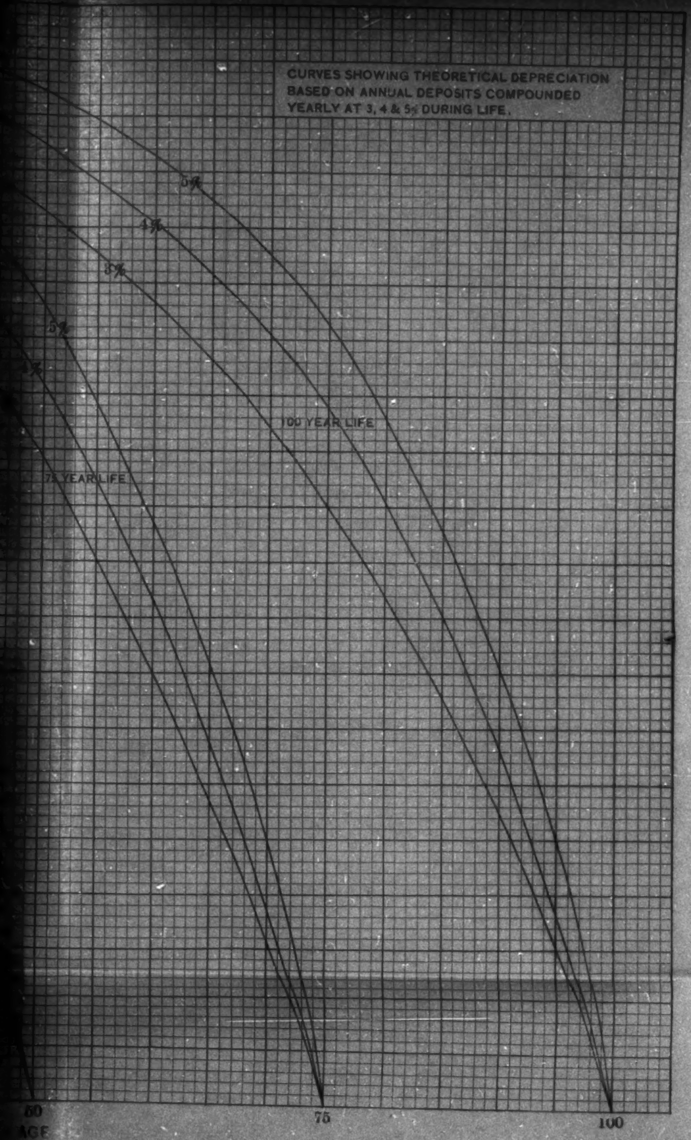
PLATE I.—



ated to electrical properties

(Ploy 1284)

As indicating the possible error in attempting to estimate "theoretical" depreciation, it is frequently found that the length of life assumed has been greatly surpassed by apparatus which is still giving reliable and satisfactory service. For example, the life of the ordinary steam engine may be taken at 20 years, but it is not uncommon to find engines still in use that are very much older than this. The writer noted, within a few weeks, that a vertical engine installed in England in 1856, had recently been equipped with condenser, supplied with superheated steam, and was still in use at 55 years of age, giving economical and satisfactory results. Cases of this kind will illustrate the necessity for personal inspection in determining depreciation and the need of experience and common sense in the application of any rules of depreciation. For apparatus still giving satisfactory service after the expiration of its assumed life, it is only fair in estimating theoretical depreciation to allow a value greater than scrap value; the minimum value of all types of engines, boilers, pumps, heaters, condensers, line transformers and shafting is, at present being taken by the Wisconsin Commission for example, at 25 per cent; generators, motors, rotaries, arc lamps, wood and iron poles, 20 per cent; station transformers, 40 per cent; storage batteries, 35 per cent and switchboard instruments and electric meters, which must be kept in a high state of repair, 80 per cent as the minimum percentage of reduction in cost for apparatus still in use though theoretically "dead."

As 3, 4 and 5 per cent are rather common rates of return on funds allowed to accrue with interest, the curves on the accompanying plate are given, indicating the values in percentages that obtain at any given time for apparatus having lives varying from 5 to 100 years. The abscissas graduated from 0 to 100 indicate the age, the ordinates 0 to 100 indicate either the percentage of depreciation to be subtracted from the cost to obtain theoretical present value or the percentage of the original value direct. To use the curves, start from a point on the abscissa indicating the life already expired, follow the vertical until it intersects with the curve marked with the assumed life of the property being considered, then follow the horizontal to the left and read from the ordinate the percentage of depreciation or the remaining present value as may be desired.

The fund that will accumulate at the end of any number of years through the annual laying aside of a uniform amount and putting that out at compounded interest, is determined by the following formula.

$$F = D\,\frac{(1+R)^N - 1}{R}$$

The sum to be laid aside annually at compound interest to accumulate a given amount at the end of a number of years is determined from the following formula.

$$D = \frac{FR}{(1+R)^N - 1}$$

where F = the accumulated amount in dollars at the end of N years.
D = the annual amount of dollars laid aside at interest compounded every 12 months.
R = the annual rate of interest expressed as hundredths of a dollar.
N = the number of years the amount is annually laid aside.

During the past few years, a large and varied assortment of figures have been offered by more or less competent authorities as to the proper rates of depreciation to be applied to different classes of physical property in accumulating depreciation funds or in the determination of present values. Some years ago the late William H. Bryan, in his paper on "The Appraisals and Depreciation of Water Works and Similar Apparatus," quoted, a number of such figures based on the authority of individuals or the technical press. These figures, while interesting and carrying the weight of individual authority where not necessarily judically approved, the writer therefore has undertaken to set out in a table, shown in the following pages, figures that have been used by commissions in rendering decisions which have in effect, largely become law.

While so used, however, they should be always considered as tentative and subject to modification for any particular case.

The figures given refer to "straight line theoretical depreciation" and have been applied to electrical properties, the life of the apparatus of which is noticeably short compared with many other classes of property, such as water works, gas plants, etc.

As will be recognized the figures given have been used for rate-making, sale and capitalization cases.

APPROVED RATES USED IN ESTIMATING THEORETICAL DEPRECIATION

(Maintenance not included)

Property	Depreciation per cent per year Straight line	Authority	Remarks
Aerial Lines	5	St. Louis P. S. C.	Union Elec. L. P &. Co.
Air Brakes	5	Wisconsin P. S. C.	
Air Compressors	4–5	Traction Val. Comm.	Chicago Con. Tract. Co.
Arc Lamps	6⅔	Wisconsin P. S. C.	
	15	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899.
	8	St. Louis P. S. C.	Union Elec. L. & P. Co.
Belting	5	Wisconsin P. S. C.	
Boilers	3½–4	Traction Val. Comm.	Chicago Con. Tract. Co.
	10	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N. Y.
(Water Tube)	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Fire tube)	6⅔	Wisc. P. S. C.	
(Water tube)	5	" "	
(Fire tube)	10	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899.
	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.
Bonds	5	Traction Val. Comm.	Chicago Con. Tract. Co.
	50% wearing value	Henry Floy	3rd Ave. Case, adopted by P. S. C., N. Y.
	5	Wisc. P. S. C.	
Breaching and Connections	3½–10	Traction Val. Comm.	Chicago Con. Tract. Co.
Buildings			
(Brick)	1½	Traction Val. Comm.	Chicago Con. Tract. Co.
	2	E. G. Connette	3rd Ave. Case, adopted by P. S. C., N. Y.
	2–4	Wisc. P. S. C.	
(Wood)	2	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899.
	2	St. Louis P. S. C.	Union Elec. L. & P. Co.
Cables			
Underground (high tension)	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
Underground (low tension)	50% maintenance cost	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Aerial lead covered)	6⅔	Wisconsin P. S. C.	
(Underground lead covered)	4	Wisconsin P. S. C.	
(Underground lead covered)	5	St. Louis P. S. C.	Union Elec. L. & P. Co.
Coal and Ash Handling Machinery	7	Traction Val. Comm.	Chicago Con. Trac. Co.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N .Y.
	10	Wisconsin P. S. C.	

APPROVED RATES USED IN ESTIMATING THEORETICAL DEPRECIATION
(Maintenance not included)

	Depreciation per cent per year		
Property	Straight line	Authority	Remarks
Condensers	4	Traction Val. Comm.	Chicago Con. Trac. Co.
	5	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N. Y.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
	5	Wisconsin P. S. C.	
	10	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899
	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.
Conduits	1	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
	2	Wisconsin P. S. C.	
	2	St. Louis P. S. C.	Union Elec. L. & P. Co.
Cross Arms	8⅓–12½	Wisconsin P. S. C.	
Engines (Steam)	3–5	Traction Val. Comm.	Chicago Con. Trac. Co.
"	5–7½	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N. Y.
"	5	Henry Floy	3rd Ave. Case, adopted by P. S. C., N. Y.
(Gas)	6⅔	Wisconsin P. S. C.	
(Steam, slow speed)	5	" "	
(Steam, high speed)	6⅔	" "	
	5	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899.
	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.
Feeders (W. P. Insulation)	Dependent on observed wear	Traction Val Comm.	Chicago Con. Trac. Co.
	6⅔	Wisconsin P. S. C.	
Foundations—Machinery	Same as life of apparatus supported	Trac. Val. Comm.	Chicago Con. Trac. Co
	Same as life of apparatus supported	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
Fuel Oil Handling Machinery	4	Trac. Val. Comm.	Chicago Con. Trac. Co
Generators	3–8	Trac. Val. Comm.	Chicago Con. Trac. Co.
	5	B. J. Arnold	Coney Island & Brooklyn, adopted by P. S. C., N. Y.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Modern type)	5	Wisconsin P. S. C.	
(Obsolete ")	6⅔	" "	
(Steam turbo)	5	" "	
	10	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899.
	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.

APPROVED RATES USED IN ESTIMATING THEORETICAL DEPRECIATION
(Maintenance not included)

Property	Depreciation per cent per year Straight line	Authority	Remarks
Heaters	4–6	Trac. Val. Comm.	Chicago Con. Trac. Co.
(Feed water, closed)	3⅓	Wisconsin P. S. C.	
(Feed water, open)	3⅓	" "	
Meters			
(Electric switchboard)	5	Wisconsin P. S. C.	
(Electric service)	6⅔	" "	
(Electric)	8	St. Louis P. S. C.	Union Elec. L. & P. Co.
Motors (Railway)	3⅓	Trac. Val. Comm.	Chicago Con. Tract.Co.
"	By inspection	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
(Railway)	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
"	5	Wisconsin P. S. C.	
	10	Arbitrators	Street Lighting controversy, Atlanta, Ga., 1899.
Paving	50% wearing value	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
	50%	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
Piping and Covering	4–4½	Traction Val. Comm.	Chicago Con. Trac. Co.
	6	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
	5	Wisconsin P. S. C.	
	5	Arbitrators	Street Lighting Controversy, Atlanta, Ga., 1899.
	6⅔	St. Louis P. S. C.	Union Elec L. & P. Co.
Poles (Steel)	2	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Wood in concrete)	5	Wisconsin P. S. C.	
(Wood in earth)	5½–8⅓	" "	
(Iron)	2½	" "	
(Wooden)	10	Arbitrators	Street Lighting Con., Atlanta, Ga., 1899.
Pumps	5	Traction Val. Comm.	Chicago Con. Trac. Co.
	5	B. J. Arnold	Coney Island & Brooklyn, adopted by P. S. C., N.Y.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Small steam)	6⅔	Wisconsin P. S. C.	
	5	Arbitrators	Street Lighting Con., Atlanta, Ga., 1899.
	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.
Rolling Stock			
(Open car bodies)	4	Trac. Val. Comm.	Chic. Con. Tract. Co.
(Open trailer bodies)	4	" " "	" " "
(Closed car bodies)	5	" " "	" " "

APPROVED RATES USED IN ESTIMATING THEORETICAL DEPRECIATION
(Maintenance not included)

	Depreciation per cent per year		
property	Straight line	Authority	Remarks
(Trucks)	3⅓	" " "	" " "
(Closed and open cars)	5	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
(Trucks)	5	" "	Coney Island & Brooklyn adopted by P. S. C., N.Y.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Car bodies and equipment)	6⅔	Wisconsin P. S. C.	
Stack	3	Traction Val. Comm.	Chicago Con. Tract. Co.
(Steel)	10	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
Stokers			
(Fixed parts)	5	Traction Val. Comm.	Chicago Con. Tract. Co.
(Moving parts)	20	" " "	" "
Storage Batteries	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
	6⅔	Wisconsin P. S. C.	
	5	St. Louis P. S. C.	Union Elec. L. & P. Co.
Switchboard and Wiring	3	Traction Val. Comm.	Chicago Con. Tract. Co.
	6	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
	5	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Modern type)	5	Wisconsin P. S. C.	
(Obsolete type)	6⅔	" "	
	8	St. Louis P. S. C.	Union Elec. L. & P. Co.
Telephones	10	Wisconsin P. S. C.	
Track (Rail Joints)	5	Tract. Val. Comm.	Chicago Con. Tract. Co.
(Ties)	5	" "	" "
(Rails)	Dependent on observed wear	" "	" "
(Special work)	Dependent on observed wear	" "	" "
(Straight and special work)	50% wearing value	B. J. Arnold	Coney Island & Brooklyn adopted by P. S. C., N.Y.
(Straight and special work)	50% wearing value	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
(Special work)	8⅓	Wisconsin P. S. C.	
(Straight Track)	5⅓	" "	
Transformers			
(Station Service)	5	Wisconsin P. S. C.	
	6⅔	" "	
	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.
Turbines			
(Steam)	5	Wisconsin P. S. C.	
(Water)	3⅓	" "	
(Steam)	6⅔	St. Louis P. S. C.	Union Elec. L. & P. Co.

APPROVED RATES USED IN ESTIMATING THEORETICAL DEPRECIATION
(Maintenance not included)

property	Depreciation per cent per year Straight line	Authority	Remarks
Wire			
Trolley Allowance of 80 5 lbs. per 1000 ft. for wearing value. of No. 1/0 wire		Tract. Val. Comm.	Chicago Con. Tract. Co.
" Allowance of 106.8 for No. 2/0		" " "	" " " "
	From observation	B. J. Arnold	Coney Island & Brooklyn, adopted by P. S. C., N.Y.
W. P.	50% maintenance cost	Henry Floy	3rd Ave. case, adopted by P. S. C., N. Y.
Trolley 1/0 under 1 minute headway	50	Wisconsin P. S. C.	
" 2/0 " 1 " "	40	" "	
" 3/0 " 1 " "	33⅓	" "	
W. P.	6¼	" "	
W. P.	7½	Arbitrators	Street Lighting Con., Atlanta, Ga., 1899.

NOTE—In connection with the above table, attention should be called to the fact that the Wisconsin Commission modifies the values indicated by the above percentages, depending on the condition of the physical property as ascertained from inspection. If the property is in good condition, 100 per cent is allowed on the basis of life indicated by the percentages in the table. If it is in fair condition, 90 per cent is allowed. If in poor condition only 80 per cent is allowed.

DEPRECIATION ACCOUNTS OR RESERVE FUNDS

A recognition of the various classes of depreciation continuously at work on physical property with the means taken to compensate for deterioration or the conservation of the original investment, whether through expenditures made as a part of regular operating expense or from accumulated funds or even through assessments on investors—provided capitalization is not thereby increased—has no necessary connection with the bookkeeping classification of the expenses or the amounts that may or may not have accumulated in reserve funds. While wear and tear have commonly been borne as a part of operating expense, it is equally important that the other classes of depreciation, or annual provision for accruing deterioration, be made a part of the cost of operation if the investment is to remain intact. In all cases involving a consideration of the expenses of keeping a property in operation, there should invariably be included allowances to cover all ultimate depreciation and replacement. For a small company or where relatively large proportions of the invested capital are locked up in few or single pieces of property, it is preferable to accumulate, in advance out of operating income, reserve funds from which to provide for all classes of depreciation. But such method may be unnecessary and possibly an inexpedient accounting complexity with large corporations, where the investments in any single piece of physical property are small relative to the total investment. The truth of the above will be at once recognized from the following illustration. If the company which erected the Metropolitan Life Insurance building had only that property, it would be essential that funds should be laid aside annually in amounts sufficient to replace the original investment at the end of the useful life of said building. On the other hand, if all the surface railways, subways and elevated railways, electric light and power companies doing business in greater New York were a single corporation, it probably would be an entirely unnecessary and useless accounting expense to maintain depreciation accounts and funds for the various pieces of physical property. It will be seen that the replacement of a considerable percentage of the trackage or a large amount of the rolling stock or even a complete power house, in the natural course of operation, would not make such draft upon the gross income or effect the annual operating expenses to such an extent as to jeopardize the net earnings or unwarrantably increase the amounts regularly expended on account of depreciation. In brief, where the properties are large enough, depreciation becomes only normal wear and tear but in any case, operating expenses should be made to provide for ultimate loss in value, whether reserve funds are accumulated or all depreciation is charged to the " wear and tear account." It is on this theory that, a large property having numerous physical elements, all deterioration becoming simply " wear and tear " and a part of operating expenses, the Receiver of the Third Avenue Railway in New York City declines to obey the order of the Public Service Commission and provides no depreciation fund whatever, simply removing deterioration when it occurs and charging it as maintenance in operating expenses.

It has been the too frequent practice in the past to regard wear and tear as the only elements of depreciation chargeable to the operating expense and to charge capital account in whole or in part with expenditures for age, inadequacy and obsolescence. The error of this procedure is now almost universally recognized and the injustice of such improper handling of depreciation to both the investor and the public being served is clearly illustrated in the following example. Assume that the depreciable property of a " going concern " represents an investment of $1,000,000 upon which the average depreciation is 10 per cent or $100,000 a year, and the interest charges at 6 per cent amount to $60,000 a year. Consider two plans of operation first, that in which depreciation except wear and tear is not provided for as a part of operating expenses and that said depreciation, *i.e.*, renewals and replacements is taken care of by the sale of additional securities. The second plan contemplates that all depreciation including wear and tear is included as a part of operating expenses. Results of the operation of these two plans will be as follows:

	1st plan capital invested	2nd plan capital invested	1st plan paid by consumer each yr.	2nd plan paid by consumers each yr.
1st year	$1,000,000	$1,000,000	$60,000	$160,000
2nd year	1,100,000	1,000,000	66,000	160,000
3rd year	1,200,000	1,000,000	72,000	160,000
4th year	1,300,000	1,000,000	78,000	160,000
5th year	1,400,000	1,000,000	84,000	160,000
6th year	1,500,000	1,000,000	90,000	160,000
7th year	1,600,000	1,000,000	96,000	160,000
8th year	1,700,000	1,000,000	102,000	160,000
9th year	1,800,000	1,000,000	108,000	160,000
10th year	1,900,000	1,000,000	114,000	160,000
11th year	2,000,000	1,000,000	120,000	160,000
12th year	2,100,000	1,000,000	126,000	160,000
13th year	2,200,000	1,000,000	132,000	160,000
14th year	2,300,000	1,000,000	138,000	160,000
15th year	2,400,000	1,000,000	144,000	160,000
16th year	2,500,000	1,000,000	150,000	160,000
17th year	2,600,000	1,000,000	156,000	160,000
18th year	2,700,000	1,000,000	162,000	160,000
19th year	2,800,000	1,000,000	168,000	160,000
20th year	2,900,000	1,000,000	174,000	160,000
* * *	* * *	* * *	* * *	* * *
50th year	5,900,000	1,000,000	354,000	160,000
	Total paid by	Consumers. . . .	$10,350,000	$8,000,000

From the above, it will be seen that, *as regards the investor*, under the second plan, he has his security unimpaired at the end of the life of the apparatus; and under the first plan, the capitalization is constantly increasing and before many years, it equals an amount several times that of the actual security. *As regards the consumer*, under the second plan he saves over $2,000,000 or 25 per cent of the cost for exactly the same service rendered him under the first plan.

APPLICATION OF DEPRECIATION

In considering the subject of depreciation, it should be clearly understood and appreciated that the term is used in two entirely distinct and separate meanings as follows:

1. *Rate of Depreciation.* In the determination of an annual rate of deterioration, which is continuously reducing the worth of the property and may be desired merely for the purpose of estimating the proper amount to lay aside yearly in reserve funds. In this use of "depreciation", there is not usually included the amount of deterioration taken care of as a part of the regular operating expenses; that is, wear and tear, the term generally refers only to the deterioration due to age or inadequacy or obsolescence—any one of these terms but not the sum of them.

2. *Total of Depreciation.* In determining the total estimated deterioration of property at a given period, which amount is obtained for the purpose of deducting it from the cost—new or reproduction—to obtain present value. In this use of the term, which is really the condition of being deteriorated, there must be included a consideration of all classes of depreciation; wear and tear, age, inadequacy, obsolescence, and deferred maintenance.

There has been such marked development and improvement in all mechanical appliances, particularly along the electrical lines, that inadequacy and obsolescence have usually come into effect before age, and in consequence, knowledge of the depreciation of all electrical properties due to age has not yet been fully established. This results from the fact that the amount of data relating to electrical properties which is available, showing by specific reference the date both of installation and abandonment through "age" is remarkably small. It should be widely collected and correlated.

The determination of depreciation due to inadequacy and obsolescence is a particularly delicate matter, it depends so largely on local conditions and especially upon individual judgment and equipoise. Inadequacy and obsolescence usually develop so quickly that very frequently the property in question becomes inadequate or obsolete within a few weeks or months, and has depreciated to scrap value almost as soon as these classes of depreciation are recognized; a space of time entirely too brief in which to apply ordinary methods of offsetting depreciation. Thus it will be recognized that an attempt to prognosticate on inadequacy and obsolescence over considerable periods in advance of their appearance is little more than a guess, even by the most experienced.

There is urgent necessity for coöperation by manufacturers, consulting engineers and operators of public utility properties for the purpose of collecting data available as to the depreciation of physical property of all classes used by public utilities. The information should be so collected as to make clear the causes of depreciation and the rate at which it has progressed. For example, wear and tear would probably have to become subdivided into maintenance and accident, otherwise a serious accident would make abnormal increase in the wear and tear deterioration. Obsolescence might be divided so as to show whether the obsolescence was caused by city ordinance or the invention of new apparatus. In obtaining age depreciation, care must be exercised that the apparatus is abandoned through exhaustion of life not through inadequacy or obsolescence.

In determining the total amount of deterioration due to inadequacy and obsolescence, only those elements of the property which have clearly and unequivocally so depreciated should be written off to this account, because as previously stated, opinions of engineers on this subject may differ honestly but widely. On the other hand, in determining the rate of depreciation for making provision covering inadequacy and obsolescence, the leaning should be to the other side; that is, the engineer should be sure to provide a rate high enough to take care of these classes of depreciation out of the operating income; for the reason that in this case, the expert is endeavoring to forestall the future and he must be conservative in protecting the property; otherwise, a sudden development of inadequacy or obsolescence will result in an abnormal depreciation account without funds to take care of same. No unfairness will result from such method of procedure as any too rapid accumulation of funds would result merely in a revision of the rate.

As the United States Bureau of Internal Revenue provides that reduction in value authorized for depreciation "shall include all expense items under the various heads acknowledged as liabilities," it will be seen that the proper understanding of the question of depreciation is a vital one for those connected with corporation management because if no depreciation fund is set up, nothing can be included in the cost of operation as necessary to provide for depreciation, as would be essential in a case involving rate regulation for example. Moreover, the State Public Service Commissions are now generally requiring the setting up of depreciation accounts and reserves on a basis to be decided by each corporation itself, thus necessitating a thorough understanding of the various phases of the theory of depreciation.

1. *Rate of Depreciation.*

"The amount that should be charged off annually for depreciation is difficult to determine. The life of the various classes of property depends very largely upon the original quality of the same, the location, the kind of usage to which it is subjected, the amount expended for ordinary or current repairs, the promptness of these repairs, and upon other factors of this character. In addition to this, there is also the question of obsolescence, or such changes as become necessary because of new inventions or because of changes in the art. In the electrical field in particular such changes are very frequent. * * * It is usually held that from 5 to 10 per cent on the investment is required yearly to meet depreciation of all kinds, depending upon conditions. When current repairs are light, it is probable that the amount to be set aside will closely approach the latter figure; when current repairs are heavy and the property kept in good condition, the former figure may be sufficient. A great deal depends upon the conditions under which the plant is operating. It is probable that the actual amount that is needed by any particular plant can be determined only through experience and by a close study of all the facts involved."*

The manner of determining the amount to be set aside for annual depreciation varies, there being three general methods recognized.

a. An estimate based on a percentage of the cost of the property being depreciated. Said percentage is such that either on a straight line or one of the sinking fund bases heretofore described it will be sufficient to provide a fund which, together with the scrap value, will replace the property in question. Such method of providing depreciation funds has been adopted for example by the Madison (Wisc.) Gas and Electric Co. The Special Master in the Columbus, Ohio case held that the amount of operating expenses chargeable to depreciation should be "five per cent of the total cost of the plant including real estate, real estate constituting but seven per cent of the total valuation."† The present laws of Massachusetts provide in respect to municipally owned gas or electric plants, that there shall be included an amount for "depreciation equal to three per cent of the cost of the plant exclusive of land and water power appurtenant thereto."

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*Decision of the Railroad Commission of Wisconsin, June 2, 1908. City of Dodgeville *vs.* Dodgeville Electric Light & Power Co.

†Columbus Railway and Light Company *vs.* City of Columbus, Report of Special Master in the Circuit Court of U. S. Southern District, of Ohio, Eastern Division, page 43.

b. A fixed percentage of the gross earnings. This is a very convenient and quite widely used method. It has the advantage of regulating the amount provided for depreciation in accordance with the gross income but a fund so provided, may have no proper relation to the deterioration actually taking place in the property because it is fixed entirely independently of the invested values. This method is sometimes taken to include wear and tear and sometimes not. The practice in this regard is illustrated by the following companies:

Name of company	Per cent of gross revenue expended or appropriated for	
	Maintenance	Replacements
Milwaukee companies:		
Railway departments	11.3	9.9
Gas, electric light and steam heat departments	6.15	8.12
United Railways Company of St. Louis	13.67	10.0
Union Electric Light & Power Co., St. Louis	4.95	16.0
Suburban Electric Light & Power Co	7.10	10.85
Detroit Edison Company and subsidiaries	6.45	10.23
Omaha & Council Bluffs Street Railway Co.	7.00	10.0
Chicago Street Railways	6.0	8.0
Philadelphia Rapid Transit Co.*		

*15% undivided between Maintenance and Replacements.

c. On the basis of kilowatt-hours output or car-miles run. For example the New York Edison Company charges off monthly for renewals and replacements, etc., an amount equal to one per cent per kilowatt hour on current sold to general consumers in addition to wear and tear. In Cleveland, five cents per car mile is provided to cover both maintenance and other deterioration. In Brooklyn, the subsidiaries of the Brooklyn Rapid Transit System allow amounts varying from 2.7 cts. to 4.4 cts. per car mile for equipment of surface roads and from 1.4 cts. to 2 cts. per car mile for equipment of either elevated or partly elevated railways; from 2.2 cts. to 2.4 cts. per car mile for way and structures for surface roads; from 1.1 cts. to 1.8 cts. for elevated or partly elevated railways, to cover not only obsolescence, inadequacy, renewals and replacements but also repairs and maintenance.

In estimating depreciation where approximate results only are desired, it is more quick and convenient to disregard scrap value and consider only cost in determining the principle to which the rate of depreciation or the amount of depreciation obtained is to be applied. The better and more refined method is to consider scrap value, which must first be deducted from the cost, and the remainder used as the principal to which to apply the rate or the amount of depreciation.

2. ***Total Depreciation.*** In order to determine at any given time the total amount of depreciation that has taken place in physical property, the cost—either original or reproduction—must be determined and from this subtract the total estimated amount of depreciation. In determining the total sum of depreciation, all articles or property included in the inventory, which are not reasonably held for future expansion of the business or held at scrap value, awaiting sale, which have been " laid aside and thrown away " and for which " new machinery and new construction has been substituted,"* together with such deterioration as results from wear and tear and existing inadequacy or obsolescence and any deferred maintenance, must be taken in order to obtain the aggregate absolute depreciation. From the cost should then be deducted this absolute depreciation in order to obtain the present real or service value of the property. If it is desired to go further than this and obtain a theoretically depreciated value, as has been done in many instances, the absolute depreciation determined, as above, must be increased by a theoretical depreciation determined by the use of estimated amounts of deterioration in accordance with curves 3, 4 or 5 of Fig. 1, or some other preferred method, to cover assumed deterioration for age and non-existent but expected, inadequacy or obsolescence.

In determining the value of the physical property at any given time, the theoretical depreciated condition is obtained by consideration of the following items:

A Cost to reproduce, or original cost.
B Scrap value.
C Wearing value.
D Wear and tear
E Age

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*People ex rel. Binghamton Light, Heat and Power Co. *vs.* Stevens Appellate Division, New York, Third Dept., March Term, 1911. (not reported).

F Inadequacy.
G Obsolescence.
H Deferred maintenance.
I Remaining wearing value.
J Present value.

$$C = A \text{ minus } B$$

$$I = C \text{ minus } \left(D + \left\{\begin{matrix} E \\ \text{or} \\ F \\ \text{or} \\ G \end{matrix}\right\} + H\right)$$

$$J = I + B$$

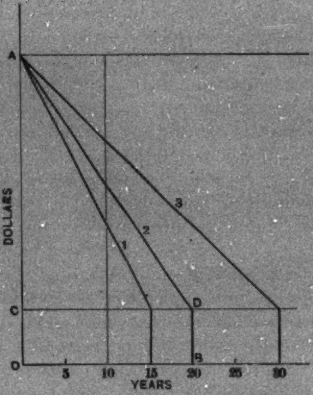

Fig. 2

In obtaining the "remaining wearing value" (*I*), it will be noted that "age" or "inadequacy" or "obsolescence" (*E* or *F* or *G*) is used in the formula, but not the sum of these quantities. The reason for this will be recognized from a consideration of the accompanying diagram, Fig. 2.

Let *O C*, that is *B D* equal scrap value, and *O A*, the cost, either original cost or cost to reproduce new. Assuming the line *O B*, that is, *C D*, represents the length of life of the property under consideration, the line 2 represents "theoretical" depreciation due to age, on a "straight line" basis (which may well be replaced either by sinking fund method—curves 4 and 5 of Fig. 1), and this element, age, would ordinarily be the rate of depreciation used unless inadequacy or obsolescence comes into effect. For the purpose of illustration, assume that line 1 represents rate of depreciation due to inadequacy and line 3 depreciation due to obsolescence. At a glance it will be seen that as the apparatus in question would be abandoned because of inadequacy some five years before, it would be abandoned for age, and as it would become decrepit and have to be abandoned on that account before obsolescence came into play, that inadequacy alone of the three classes of depreciation under consideration is to be taken into acconut. At a given period, say 10 years, from installation, the vertical distance from the point indicating 10 years, will indicate by intersection with the proper curve, the theoretical amount of obsolescence, age and inadequacy; but the sum of these would be greater than the original cost showing clearly that the depreciation which will first cause the abandoning of the article in question, should alone be considered, in addition to wear and tear, and deferred maintenance.

The above sets forth the general method of applying the theory of depreciation when the proper and total amount of deterioration is obtained, without regard to whether one is considering the sales value, service value, or theoretical depreciation. It is office work entirely; but on the other hand, the determination of the amount of depreciation in a given property is not office work and not principally so. All authorities agree that no exact estimate of the amount of depreciation of physical property could be obtained without personal visual examination supported by broad experience and sound judgment; and it is for this reason, because of the personal equation, that experts differ so widely as to results.

The fallacy of attempting to determine absolute present value by deducting from the cost to reproduce new or original cost, the value at a given age, as indicated by curves 3, 4 or 5, in Fig. 1, will be at once apparent from a consideration of the following:

Assume that the " present value " of a given piece of property is desired, which has an estimated life of 20 years, ten years having already expired. If at the several points there be taken on curves 3, 4 and 5, respectively represented by the "straight line" and " sinking fund " methods, the depreciation of the same property at the same time, we have three decidedly different values depending on which curve is used, and if three different engineers estimating the present value, each adopt a different curve, they are prepared to go on the stand and testify to three different values of the property in question, which of course, is an absurdity and makes them ridiculous. As a matter of fact, the apparatus in question can have only one value or another neither of which will depend on the method adopted for accumulating funds for which all these curves are useful; but upon whether the apparatus is being valued for what it would bring when sold for use elsewhere, as shown by curves 1 and 2, or its worth for use in connection with the purpose for which it was installed, as shown by curve 6.

Very many authorities agree that in making an estimate of the amount of depreciation effective in any property, "used or useful," there should at least be included in the amount to be deducted, an estimate of the amount of wear and tear, deferred maintenance, if any, also scrap value of property that has been worn out or superseded as well as inadequate or obsolete property provided it is still inventoried.

> "Where equipment not actually part of the producing plant has been retained and serves as an emergency or reserve unit, it is properly included as property used and useful in serving the public. Equipment, however, which has been cast aside for larger units, more adapted to the present use of the plant, or which has been abandoned as impracticable, cannot be included as a part of the valuation serving as a basis for adjustment of rates."*

The only allowable exception to the inclusion of inadequate or obsolete property as a part of depreciation, is where inadequacy or obsolescence has so suddenly and largely effected a property that its earnings have not permitted the writing off at the time or since such developed depreciation; then in such cases it may be that capitalization or earning basis should not be reduced by taking account of any such depreciation. This principle has been established by the United States Circuit Court where it held that in considering the cost of reproduction new, $2,000,000, the value of old street railways that had been replaced, should be allowed for and included.†

A similar view was expressed by the Supreme Court in the opinion written by Justice Brewer in 1894.

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*Decision and Order of Railroad Commission of Wisconsin, June 17, 1910. In re-Application of the Darlington Electric Light and Water Power Company for Authority to Increase Rates. Valuation of Property.

†U. S. Circuit Court in the Milwaukee Electric Railway and Light Co. *vs.* City of Milwaukee, 87 Fed. 577.

"It is not always reasonable to cast the entire burden of the depreciation on those who have invested their money in railroads. Take the Union Pacific Railway, for illustration. At the time the government created the corporation, to induce the building of this transcontinental road through a largely unoccupied territory, it loaned to the company $16,000 a mile; taking as security therefor a second lien on the property and granting to the corporation the right to create a prior lien to an equal amount, which was done. There is testimony tending to show that the road in Nebraska could be built to-day for $20,000 a mile. Would it be full justice to the government, would it satisfy the common sense of right and wrong, would it be reasonable, for the State of Nebraska to so reduce the rates that the earnings of the road would only pay ordinary interest on $20,000 a mile, and so, the holders of the first lien being paid their interest, the government be forced to be content with only interest on one-fourth of its investment? Or, to put the case in a little stronger light, suppose the promoter of this enterprise had been some private citizen who had advanced his $16,000 a mile as the second lien, and that the road could be constructed to-day for only $16,000 a mile. Would it be reasonable and just to so reduce rates as to simply pay to the holders of the first lien reasonable interest, and leave him without any recompense for his investment?"*

Whether or not "theoretical depreciation" should be included as part of the total depreciation in determining fair value of physical property is a mooted question. The Public Service Commissions have rather leaned to the opinion that such depreciation should be considered in determining fair value. On the other hand, many, if not all, of the court decisions are against such inclusion of theoretical depreciation. This is indicated by the decision of the Supreme Court sustaining the Master's opinion in the famous Consolidated Gas case of New York City. The Master says, regarding the testimony of the expert for the plaintiff, Mr. Marks, and for the defendant, Mr. Mayer, that

"Mr. Marks did not particularly regard the extent of depreciation actually existing, but assumed a theoretical deterioration of the supposed life of the plant. He testified:

> 'Depreciation results from several causes. The most ordinary one is decay or wear and tear, as observed. There is another factor which is inadequacy, owing to the increase of the business. There is also another cause of depreciation, obsolescence, which is due to the changes in the arts and in the methods and in the general growth of scientific knowledge; if a works built at a certain period is kept in perfect repair, meaning by that, always restored to their original condition, and in good working condition, there remains, assuming that, a depreciation due to both obsolescence and to inadequacy.'

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*Ames *vs.* Union Pacific Railway Company, 64 Fed. 165.

"In this view he made estimates on the theory of the cost of final replacement to cover such inadequacy or obsolescence, ranging from 25 per cent to 60 per cent and based on a supposed life of 120 years for the plant. The discrepancy between his valuations and those of Mr. Mayer is largely due to their different methods of estimating depreciation. He said:

> 'Mr. Mayer does not differ largely from my now figures of structural cost. You may say for all ordinary purposes they coincide, with the exception of the gas holders and even there they do not differ largely. It is the question of depreciation entirely.'

"As will hereafter appear, it is proper in the administration of a manufacturing plant to take depreciation of the character above described into account and provide against it by setting aside a reserve fund from current earnings. For the purpose of determining present value, however, particularly on the basis of cost of reproduction, the method followed by Mr. Marks does not commend itself. It appears from the record, without substantial dispute, that while certain of the plants and apparatus may not be in perfect repair, they are as a whole, in efficient operating condition, and that a large proportion of their capacity is represented by the latest pattern of water gas apparatus installed within the last few years. * * *

"The fact thus being that the plants are in good order and operating efficiently, it does not appear reasonable, for the purposes of this case, to charge them with a theoretical deficiency so great as, if actually existing, would make their successful operation a practical impossibility. An estimate of depreciation like those of Mr. Edgerton and Mr. Mayer, based on a detailed examination of the property as it stands to-day, affords in my opinion a more fair and practicable method to be followed in determining its value."*

From the above, which is probably as full an exposition of the proper basis for estimating depreciation as ever approved by the Supreme Court, several important points are made clear:

a. Depreciation should be determined by personal inspection rather than by theoretical estimate.

b. Property that is in good order and operating efficiently, although not new, should not be depreciated, at least in rate cases.

The decision of the Supreme Court in the Consolidated Gas case has not been given due consideration in the matter of depreciation as against the same court's decision in the Knoxville Water case, although both decisions were rendered the same day. In the writer's opinion there is no contradiction between these decisions as to the meaning of "fair value" or method of allowing for depreciation if the decisions are fairly interpreted.

An examination of the Master's Report in the Knoxville case shows that in obtaining the value of the property on which he estimated the rate of return, he used higher unit prices than the average; he included over $22,000 worth of service connections, which had been donated by the water consumers; also $2,000 as a "contingent allowance for bad bottom," and he did not make any deduction for wear and tear, deferred maintenance, inadequacy or obsolescence, adding the sum of both complete and incomplete depreciation to the estimated value of the surviving plant in order to obtain the value which he used as the basis of rates. As the Supreme Court clearly states, it did not attempt to decide how much of the Master's value of the tangible property should have been diminished by the depreciation which the property had undergone, stating it would be improper that "the amounts of complete and incomplete depreciation should be added to the present value of the surviving parts" in order to obtain the total plant value to be used as a basis of rate making. This position is further explained by the following quotation:

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*Master's Report, Consolidated Gas Co., of New York. Filed June 24, 1907.

> "The cost of reproduction is one way of ascertaining the present value of a plant like that of a water company, but that test would lead to obviously incorrect results if the cost of reproduction is not diminished by the depreciation which has come from age and use."*

Is it not clear that in this case the Supreme Court consistent with its decision in the Consolidated Gas case was pointing out that such depreciation as that due to "complete" deterioration, "use" that is, wear and tear, also deferred maintenance, inadequacy, obsolescence, age—in the sense that the life had completely expired—must be estimated and deducted from cost in determining fair present value. If not, and the Knoxville Water case properly construed means that present value is to be obtained by deducting the theoretical depreciation from cost, how does the Supreme Court explain its decision in the gas case? By what method is theoretical depreciation to be determined? At which month in the life of the physical property which extends over years is the present value to be estimated? Assume that the life of a complete property is 20 years, then at the end of 19 years and 6 months, the present value of the property would be almost nil and the rates thereon would include practically nothing in the way of return on the property, a year thereafter the property being entirely replaced and new,

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*In the Knoxville Water Case (City of Knoxville *vs.* Water Company, 212 U. S., 1.)

the rates would be incomparably higher and between these two extremes, the rates will fluctuate depending on the year or the month in which the present value is estimated. Consider two surface railways running out parallel avenues from the centre of a city to the suburbs, both alike in construction but one ten years old and the other put in operation within a year. If theoretical depreciation is considered the present values of these two properties are quite different, the older road being worth appreciably less than the new road, although the original cost of installation may have been the same in both cases. Under such circumstances, is the older road to be allowed to charge only a four-cent fare, assuming that that gives a fair return on the estimated present value, while the new road must charge a five-cent fare for the same return on its estimated value? What would be the result practically of such method of fixing rates? The old road would be swamped with business and the new road would be unable to maintain its earnings. Again, the theoretical present value of the property of a lighting company might be found to be 50 per cent of the cost new but such value would not properly represent its worth in service to the public because it would probably be in such poor condition that continuous and satisfactory service could not be rendered and the real worth and service to the public would be very much below 50 per cent. On the other hand, through extravagant management, and the replacing of partly worn out apparatus before economically necessary and the incurrence of abnormally high maintenance charges in order to maintain the theoretical present value of the property at say 90 or 95 per cent, there would result unnecessarily high operating expenses and unwarrantable charges upon the public merely for the sake of maintaining a theoretical high present value on which a fair rate of return must be allowed. A property of this kind maintained at an abnormally high present-value worth, would be of no greater service to the public than one of which the present-value worth might be only 75 per cent, whereas the burden to the public in maintaining the former property would be very much higher than the latter. Can such fanciful and variable bases be intended by the Supreme Court to be taken as those on which rates are to be estimated and regulated? Such conclusion would be illogical, unreasonable and unfair. Provided a property is kept in good order and at 100 per cent working efficiency so as to render service to the public equivalent to that of a new plant, the question of rates or value of property in its service to the public has absolutely nothing to do with the amount of reserve funds the corporation may or may not have accumulated. The value of any physical property, as must of course be recognized, has no relation whatever to the amount of money a corporation may have to its credit in the bank, nor have rates for service as far as we have ever heard, been based on the amount of a company's surplus or reserve funds. While the engineer must be quick to recognize loss of value where it actually exists and to make deductions for property that has been worn out or superseded, he should not be misled into including hypothetical or academic values.

The confused state of mind that prevails with regard to the application of depreciation in determining present value, results largely from the misapplication of principles established by the Courts in rate cases. These decisions expressly provide that allowances to cover the deterioration of all sorts including ultimate replacement, are to be provided out of operating income; citations supporting this view are too numerous to mention but a quotation from the Knoxville Water case, referred to above, is particularly pertinent in this connection.

> "The company is not bound to see its property gradually waste without making provisions out of earnings for replacement. It is entitled to see that from earnings the value of the property invested is kept unimpaired, so that at the end of any given term of years, the original investment remains as it was at the beginning."*

In view of the perplexed state of mind and contradictory decisions that exist, the clear thinking and fair decision of the St. Louis Public Service Commission is refreshing. The quotation is a brief summary of their method of determining present value—which did not include deductions for mere age—in fixing fair rates to be charged by the Union Electric Light and Power Company of St. Louis.

> "In depreciating to arrive at the present value of the depreciable property, the Commission does not consider it fair to make deductions for anything but the present physical condition, and for items where it is plainly apparent that the property has become obsolete or inadequate. The usual estimate of the life of different parts of a public service property, so far as they deal with obsolescence or inadequacy, are extremely problematical and these elements should not be generally taken into account in determining present value."†

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*Knoxville *vs.* Water Company (212 U. S., 1).

†Report of St. Louis Public Service Commission to the Municipal Assembly of St. Louis on Rates for Electric Light and Power, 1911.

FIFTY PER CENT METHOD

A quick and it seems to the writer a very fair method of obtaining the theoretical depreciation of certain classes of physical property, has been used in some utility appraisals and may be called the "fifty per cent method." This system was originally suggested from a consideration of the mortality or life tables used by the Insurance Companies, which give average results. While it is never desirable to determine depreciation without inspection of physical conditions, the "fifty per cent method," by reason of its simplicity and prompt derivation of results and its freedom from individual judgment or bias has strong claims to pronounced advantages and in any case may be a desirable check to other methods. It has been used by Professor M. E. Cooley in connection with his figuring of depreciation in the Michigan State Appraisal, by H. P. Gillette in the appraisal he conducted for the State of Washington, by B. J. Arnold in appraisal work he did for the Public Service Commission of the First District of the State of New York and by the writer in connection with reorganization of the Third Avenue Railway in New York City; it has I understand also been approved by the Master Car Builders Association in connection with the appraisal of rolling stock. It will be at once recognized that to apply this method of estimating depreciation, it is essential that the property being depreciated shall include a large number of similar parts, for example, in its application to a transmission line, the poles should all be of wood with similar character of cross arms and of approximately uniform dimensions and the installation should have been made such a length of time that the annual expense for maintenance and repair is practically uniform. This condition is only reached after property has been in use a considerable length of time, certainly five and preferably ten or fifteen years in the instance cited, so that the parts are being renewed piecemeal and it is possible to find some poles, cross arms and braces just ready to be replaced, others new, having been replaced within a few days or weeks and between these extremes, all stages or conditions. Another class of property to which this method of depreciation may be applied is rails, ties, the smaller sizes of transformers, meters, arc lamps, boiler tubes, street railway motors, etc. It will be seen that this method of determining depreciation will be fallacious if the installation does not consist of a large number of similar elements or has not been in use for a sufficient length of time to permit the repair account reaching its normal maximum, which it would not do unless practically all parts have been renewed once and renewals are constantly taking place; hence, it could not be applied to the buildings of a corporation which owned few buildings and probably not even to engines or generators because usually they would be too few in number—except for the very largest organizations—to permit their being replaced without abnormally effecting the amount annually appropriated on account of depreciation. The net result of the application of the fifty per cent method is at once apparent, fifty per cent of the cost less salvage, will be immediately written off as depreciation.

DEPRECIATION OF CONTINGENT PERCENTAGES

The percentages added to structural costs to cover engineering, incidentals, contingencies, etc., in order to obtain physical values have usually been considered an inherent part of the cost of the physical property and treated as such in connection with the depreciation of the physical property. With certain parts of the property, this is undoubtedly a correct procedure and for the sake of simplicity and consistency may be recommended; but as a matter of fact, the original engineering investment in certain parts of the physical equipment, for example, road-bed and track, still remains there and is as much a part of the property as the real estate, although the rails and ties, which have been cited, may have been many times relain and paid for as a part of operating expenses. It would be no more unreasonable to leave such investment percentages undepreciated than it is to depreciate the physical property entirely independent of development expenses or going value which seldom, if ever, has been practiced. It has been held by some that the discount on securities should be written off at the same rate as depreciation of the physical property; but the more usual plan is to amortize such costs at a lower rate, determined by the life of the bonds. In come cases, it may not be advisable to amortize such investments of this character at all, justification for which is evidenced by the decisions of the Public Service Commission of New York, First District, in the Third Avenue Railroad case where they did not depreciate at all the original investment for removal of obstructions such as pipe lines in the streets, paving over obstructions, etc., although these expenses were incurred for work necessary but not apparent after completion as the pipes, etc., were left outside the right-of-way.

Summary and Conclusions

In concluding this paper, which the writer does not pretend by any means exhausts the broad subject of "depreciation," it is desirable to summarize the principal features and conclusions herein outlined.

1. The necessity for a more general agreement on and uniform use of the terms used in considering and discussing the subject of depreciation, by the engineering profession.

2. The rate of depreciation adopted in estimating and providing for accruing depreciation, must not be confused with the total sum of depreciation in physical property, which is an estimate for a given time.

3. The difference between absolute and theoretical depreciation should be recognized and the amounts of each separately estimated and considered.

4. Theoretical depreciation must be assumed and provided for as a part of operating expense if capital is to remain unimpaired and rates are to give the maximum service at the minimum expense.

5. Service value, determined from the consideration of the "absolute" not the "theoretical" depreciation of physical property, is to be used, in connection with certain proper nonphysical values such as development expense, going value, franchises—if any—*et cetera*, as the basis on which rates are to be fixed, capitalization allowed and taxes assessed.

6. While usually preferable there exists no necessary reason for always writing off certain costs such as engineering, incidentals, *et cetera*, at the rate at which the physical property of which they are an inherent part, is depreciated.

7. Development expenses bear no fixed relation to the cost of the physical property and their amortization has no necessary relation to the rate of depreciation of the physical property.

8. The amount of depreciation of physical property can only be accurately determined by inspection on the part of competent and conscientious engineers.

9. There exists an urgent demand for coöperation among engineers, manufacturers and service corporations for the intelligent collection and correlation of data on which to properly base estimates of depreciation.

DISCUSSION ON "THE RESPONSIBILITY OF ELECTRICAL ENGINEERS IN MAKING APPRAISALS," "DEPRECIATION AS RELATED TO ELECTRICAL PROPERTIES." CHICAGO, JUNE 27, 1911.

Bion J. Arnold: The question of the relationship of public utility corporations to municipalities is one to which I have given more or less attention during the past eight years, and consequently I may, perhaps, say something on the general question that will bear upon the first paper, and possibly point out one or two things with reference to the second paper which may be of interest.

In the first place, I quite agree with the first speaker, and with our President as outlined in his remarks this morning, that the engineer can perform no higher service to his profession or to the community than by becoming interested in this subject and endeavoring to get the public mind clear, or help it to make up its own mind as to what is a fair disposition of the various questions that come up before the various individuals composing the public and the public utility corporations. We are all familiar with the fact that the state in which the public mind has been for some years past is due largely to the fact that the corporations, or those having them in charge, did not look upon the public's side of the question as liberally as they should have done, at certain periods of the corporation's existence, and the fact that these oversights were made, created in the public mind a distrust of the methods adopted in certain instances by corporations. I think we will all admit that that supposition on the part of the public was fair in many instances, although on the other hand, it is not fair to assume it was always true of all corporations, but the fact exists, that the public got into that state of mind. When the public finally got in a position to require the corporations to do things which the corporations had not previously been doing, the public went to the other extreme, and exacted of the corporations things which were equally as unjust to the corporations as the injustices which some of the corporations had been perpetrating on the public in the past.

Fortunately, during the past three or four years the public has become more or less educated on the subject, and is treating the corporations more fairly, because the public is analyzing these questions more thoroughly and understands them better. I think this better feeling is due, first, to the fact that the public wants really to treat the corporations fairly, if it is sure that the corporation will treat the public fairly, and, secondly, to the fact that many members of this profession and other engineering professions have taken a hand in solving these questions and have been instrumental in educating the public mind as to what is fair between the public and the corporations.

Now, on the question of franchise values. Our original methods were largely wrong. All of us 20 or 25 years ago were engaged—

I say all of us, many of us, by the manufacturing corporations or the public utility corporations—in creating the electrical enterprises; some of them not electrical, because we are not all electrical here, but most of us were engaged in creating the electrical enterprises some of which have come up for public criticism since that time. We all went ahead at that time on the theory that the franchises were valuable, and therefore they would stand capitalization, and they were capitalized. Consequently, the public was required to pay a return upon not only the real cost of the property, but also on a fictitious cost, or an assumed cost, or an assumed value, rather, instead of cost, on these franchises. Now, taking into consideration the pioneer period during which these enterprises were created, it is not perhaps unfair to say that these corporations were entitled to an excessive profit upon the actual physical value of the properties of that day, and that, therefore, they were justified in assuming that the franchise had value, and in paying a rate of return upon these franchise values—I do not know that I will say franchise values, but partly upon franchise values and partly upon capitalization that it was necessary to put into the properties to replace the parts of the property that became obsolete during the rapid changes in the state of the art, thus introducing into the capitalization of the companies not only the question of franchise values, but also the question of obsolescence.

My position on that matter for the past three years, after having had five years to think about the subject and come to conclusions that I thought satisfied my own conscience is—that a public service corporation is justly entitled to have more than a fair return upon the actual money put in under such conditions, namely, pioneer times—that a company is entitled to excessive profits for those times, or if it should not make these excessive profits, it is entitled to live long enough to make a good profit not only during those times but also during its life, so that the people who put the money into the enterprises under great stress and great risk, shall make more than ordinary returns upon their money, for having taken the risk of the venture, provided that when the company has earned and paid to the stockholders this profit, all excess over a fair return upon the value of the property thus performing the service shall be put into a fund to gradually amortize obsolescence and other values previously carried in capital account but representing no real property. I have recently put this plan into practice in one the of largest cities in this country—and got the corporation, also one of the largest, to agree to it. The fundamental principle underlying that theory is this: That the public should pay, for instance, to a street railway corporation, the actual cost of producing the service which is given to the public, plus a fair return upon the actual capital necessary to create the property, and also that necessary to continue its operation. In the case of early railroads or railroads created under pioneer conditions I would give them much more than the present rate of interest; and in cases where the properties have operated at a loss during the earlier periods, I would allow the companies to maintain in their capitalization the actual cost of the properties plus these early losses, and I would allow them to continue to earn a higher rate of interest than what is now usually considered a reasonable rate on money, until they have earned back out of the property these early losses, and a liberal return upon the actual money they put into the property, which would cover not only the present physical value, but also the cost of such machinery and material as has become obsolete during the creation and operation of the property up to the present day.

This is upon the assumption that from now on the company is going to be regulated as to its rate of return by public service commissions or by other state or municipal authorities, and thus be prevented from earning excessive returns out of which to recoup their early losses—because the corporations when they went into these enterprises assumed they were going to be able to operate them long enough to get their money back, and make something more than an ordinary rate of return otherwise the parties furnishing the money would never have gone into the enterprises and operated them at a loss during the early periods. Now, the public may state its proposition in two ways—*i.e.*, it may say we will allow you to make large returns up to the present, but from now on we are going to regulate your rates, so that your return will be only the ordinary interest on your present investment. I believe that if the public is going to regulate from now on, it should see that the past losses of the companies are taken care of and that the capital that went into the enterprise in the past should yield a liberal rate of interest up to date, and if the company has been honestly managed and has not earned that interest and also enough to make up its early losses and return the capital represented by obsolescence, that this capital should stay in the capitalization until the company earns it out, and from that time on the company should accept what is considered now a reasonable rate of return upon the actual value of the property then providing the service and also that from that time on, all earnings over and above that rate of return should be put into an amortization fund, to gradually retire this capitalization represented by obsolete property, purchased during early operation, and other development expenses. I hope I made myself clear upon that point, because I believe it is fundamentally right that the public should pay the cost, plus a fair return, to the company that produces this service. It is right, when the company has earned back its money which it took to produce that service, that the public should pay a return simply upon the actual value of the property which is producing the service, assuming that the people who went into the project in the earlier days have made a good, liberal return on the investment.

Therefore, our present methods, or rather the methods of some of us who are engaged in endeavoring to straighten out some of the present difficulties, are as follows: We assume that these corporations have been organized under the above conditions, and have operated up to the present time, some of them with great success, and some with indifferent success. Those which have been operated with indifferent success are entitled to the consideration which I have mentioned, but those which have operated with great success, however, and have taken out of the property a good liberal rate of return, are not allowed to carry in capitalization this excessive capitalization any longer. In other words, if the records of the property show the property has been honestly and well managed and the rate of return, taking gross receipts, and deducting operating expenses, have not been enough to pay a good rate of return on the investment, the amount spent for obsolescence and for early losses should be kept in the capitalization, but if the records show that the company has made a liberal return on its investment and that the extra money has been declared in excessive dividends instead of creating a depreciation fund out of which to rehabilitate the property, then I say such a corporation has no right to claim the benefits of the plan just suggested, and it should be judged on the physical value of the property as it exists today.

That is the method which was applied to the valuation of the Chicago properties some five years ago, namely, that these properties, especially one of them, had earned excessive rates of interest for years, some of them as high as 35 per cent upon the money they cost, and consequently the people who owned the property received back many times over the money they put into them, and consequently there was no hardship when they had to accept a depreciated value of the property, namely, a value which represented the real property in existence, with the understanding that from now on, when the property has been rehabilitated and firmly established in such a manner that the securities of the properties are absolutely reliable, as the pioneer days are gone, the people who now put money into or have money remaining in these properties should be willing to accept a reasonable return from this time on, be that five, six, seven or ten per cent, whatever you agree upon—but it cannot be 25 per cent or 40 per cent, or something like that, because the money now invested in the properties, is invested in a stable investment, and we must accept it as such and the public utility corporations should recognize that those of them who have accepted this view of the situation are the ones who are getting along most successfully in our municipalities today.

On the question of values, in making a valuation of the physical property, of a public service corporation it is right, in my opinion, to determine, first, the cost to reproduce the property new, and in that cost to reproduce new must be considered not only the actual value of the physical property that you can go out and find, but you must consider also interest during construction, engineering expenses (usually five per cent) legal expenses applicable to construction only—I do not mean attorney's fees incurred in the creation of the company, or the securing of franchises, or anything of that kind but only those applicable to construction work alone and a reasonable contractors' profit.

When fixing the rate a corporation should be allowed to charge for service there are sometimes other expenses which should be included in its development expense, such as preliminary technical expenses, legal expenses during the formation of company not connected with construction expense, cost of consolidations and reorganizations, sometimes a reasonable promotor's profit, supersession of equipment due to the rapid advance of the art, reconstruction due to unforeseen contingencies, brokerage, discount or premiums on securities, and sometimes franchise and " going " values, including losses during early operation, all of which should, however, eventually be amortized and eliminated from the value of the property upon which the public should be expected to pay a rate of return, although it is but fair that the company should have time to earn this amortization fund.

These are what are known as development expenses, usually running anywhere from 10 to 25 per cent of the cost to reproduce the physical property new. Some companies will contend and say it should be as high as 35 per cent. I never yet found a property where I thought such a percentage should be allowed, but have found some where 25 per cent was fair, some as low as 12 to 15 per cent, some 22 per cent, and I think that from 20 to 25 per cent is not ordinarily an unfair figure to add an order to determine the actual cost of reproducing new the physical property.

My time is short, and I have endeavored in a general way to outline my judgment regarding the subject of Mr. Byllesby's paper, which is a very valuable discussion of the general subject.

In regard to Mr. Floy's paper, he makes the point that the engineer must know for what purpose the valuation is being made, and states that so far as the value of the property to the owning and operating company is concerned, that is, for its use, a very low rate of depreciation should be considered. I am not so sure that that is correct. I maintain and always have, when you are considering a question of rate making, that the company asking for the rate, should be allowed a rate based upon the cost to reproduce the property new, taking into consideration the development expenses which I have mentioned, and that a condition precedent to that valuation, requires the property to be in first-class condition so as to be able to give first class service and if the property is found to be in bad physical condition, that the company has no right to ask that the rate be based on the cost to reproduce new, unless the company has in its treasury, or has somewhere a depreciation reserve fund, such as we have in Chicago, provided of course it has been able to earn such a fund sufficient to put the property in first-class condition, so as to give a first-class service, which is what you require of it, and which is the condition you require it to be kept up to in order to entitle it to the rate you gave it.

Many communities will attempt to fix a rate upon the depreciated value of the property. I think that is a short sighted policy from the standpoint of the public, because if the rate is fixed on that value the company has no chance to raise enough capital to put its property in first-class condition, to give first-class service, and consequently the rate should be based upon the capitalization to reproduce the property new, or on the present depreciated value of the property, plus enough to put it in first-class condition, and that money must be in the treasury of the company, or in a fund for that purpose.

W. F. Wells: Mr. Floy has covered the subject of depreciation in such a broad and comprehensive manner that he leaves almost nothing to be said. However, I would like to voice my approval of the statement he makes, to the effect that in estimating the value of the property, only absolute depreciation be considered, and not any theoretical value of depreciation. I think that property which is in good order, and operating efficiently should not be depreciated when rate cases are under consideration. In other words, any company which is maintaining its property in first-class condition, so that its original utility is unimpaired, should not be compelled to depreciate the value of that property for the sake of rate making.

As to Mr. Byllesby's paper, I have heard one or two engineers take exception to the manner in which he has treated the question of replacement value of underground subways over which new pavements have been laid. A company is entitled to this increment value just as much as it is to the increment value of real estate or any other property. Companies frequently install subways in advance of new pavement in sections of cities where for years to come the gross revenue will not pay the fixed charges, but they do this on the idea that the difference between the original cost and the replacement value after the new pavement is laid will in part offset these carrying charges, such as interest and taxes during the time of nonuse.

Regarding the general subject of appraisal work, one of the most difficult and laborious features is to obtain physical inventory of the underground system of an electric light company.

I had occasion this spring to make a complete inventory of the underground property of the Brooklyn Edison Company, and the method followed may be of interest to some here.

The property was all recorded graphically on maps and records, contained in some twenty large volumes. On each page of these books were shown the details of the sub-surface structures in about 500 lineal feet of street, including the subways, man-holes, cables, Edison tubes, junction boxes, etc. The problem was to tabulate and summarize the amount of each type of construction.

I determined that the Hollerith system, such as was used by the United States Government in tabulating and summarizing the statistics of census reports could be made the most satisfactory. We had all the necessary perforating, sorting, and automatic calculating machines, which were in use for analyzing our output and revenue, and after thorough analysis of our underground system, I found that by slight modification, it was possible to adopt these machines for making the inventory. The data on the record books was transcribed to special forms which were prepared, using one sheet for each page. In order that these data may be perforated on the templet cards, for the sorting and adding, it was necessary to indicate all descriptions in figures or key numbers. Every street in the city was given an arbitrary number, which, with the sheet number, completely indexed the sheets.

All types and characters of subway construction were indicated by nine figures, the first two indicating the number of ducts in the bank; the third, the material, such as tile, fibre or iron pipe; the fourth, the number of ducts wide in the trench. Two more figures showed the distance from the top of the duct bank to the top of the street pavement, the character of which was indicated by another figure. Two more showed the date of installation, thus; 16.5.4.06.1.07 indicated 16 ducts of tile laid four wide, and therefore four deep with six feet of cover between the ducts and top of an asphalt pavement during the year 1907.

For man-holes two digits showed the perimeter of the hole; the third indicated the character of cast iron head employed; two more the depth of the hole; another the material, whether brick or concrete; another the type of paving and two more the year installed.

For cables the first digit indicates the character of insulation; the second the number of conductors; the third the voltage; two more the size of conductors, and two more the year installed, thus: 4.3.2.2.5.07 indicates a lead covered paper insulated cable having three conductors for use on 6,600 volt service, each conductor being 250,000 cm. and installed in the year 1907. All quantities were naturally expressed directly in figures. After the record sheets were prepared, of which there were 3,800, some 33,000 cards were perforated, the operators being able to punch from 200 to 400 per hour.

These cards were of two kinds, one showing number and character of services, quantity and style of subway and duct feet occupied, the other showing the number and type of manholes, and length of various cables installed.

These cards are then placed in the sorting machine, which may be set to select any type of construction, after which the adding machine summarizes the quantities.

These cards and record sheets, with additions and withdrawals, now form a perpetual inventory of our underground property and are so indexed that any card may be checked at any time.

John W. Lieb, Jr.: I think that the Institute is to be congratulated for having had presented to it these two papers which are somewhat afield from the usual line of papers which have been presented before the Institute heretofore. We all of us, whether engaged in the railroad field, or the transportation field, or the electric lighting field, must sooner or later come face to face with these problems, and it is of the utmost value and importance that we shall have a fairly general view and grasp of the situation. If this is not the case, when we come to represent our respective interests before public bodies, such as public service commissions, or regulating state or municipal bodies, we will find it necessary to make our views known, perhaps inadequately, perhaps incompletely, through the medium of our attorneys.

Now, all of us who have had experience in trying to deal through our sister profession with technical matters must recognize the extreme difficulty and the unsatisfactory method of having to deal through a representing medium commonly unfamiliar with the technical expressions and the technical requirements of these cases. Therefore, I say that these gentlemen have done a real service to the Institute in calling the attention of the members to these questions, so that they shall become well informed and have presented to them in a compendious and complete presentation the gist of these matters, and Mr. Floy in his paper has presented what is a fairly complete list of definitions which certainly should prove extremely useful.

Unfortunately, in presenting matters on a subject of depreciation rates of depreciation are given in tables. It is very easy to apply them in a way to make them misleading. These rates of depreciation are usually based on the exhibition of the physical life of the properties of the apparatus, without taking into consideration the necessity of a very much shorter career, due to supercession, conditions of obsolescence, etc., and it is unfortunate that tables of depreciation do not specify that they do not cover obsolescence and do not cover any supersessionary reducing time limit. If you will refer to the table given in Mr. Floy's paper, and what follows, you will see how evident this is. Under arc lamp, for instance, the fourth item, rate of depreciation in per cent per year for arc lamps is six per cent. Now, we all of us who have been engaged in this business know how thoroughly inadequate any such allowance as that would be with these rapid changes that are going on in this field. The same thing would apply, for instance, to the rate of six per cent, or 6.5 per cent for electric meters.

Now, we have had the assistance in furthering this rapid voyage from the operating room to the scrap pile of very many of the members of this Institute, and they are partly responsible for this continuous cycle of improvement. It is, of course, to this continued cycle of improvement that we owe the immense expansion which this industry has had, but it also should be recognized that this continued cycle of journeys, of rapid journeys, from the operating condition to the scrap heap, should have its proper expression in what is the real and proper rate of depreciation, and if tables of depreciation do not include supercession or obsolescence they should so specifically state.

I was very much interested, indeed, to hear Mr. Arnold's statement of his views in regard to a matter of the very utmost importance to all public utility corporations, that is to make a reasonable and proper provision for disappearing assets, the physical assets which in the course of these consolidations and mergers that have already taken place, have disappeared, and it is a most unfortunate condition, for which our present financial conditions and lack of explanation is largely due, that the public is misinformed, and considers that these disappeared assets are denominated by some of our friends as " water ".

Now, gentlemen, in bringing these vast properties together, and in order to give the public the advantages which they have received in large measure by bettered service or lowered rates, it has been necessary to scrap enormous quantities, enormous parts of the apparatus that have been functioning in some of these smaller corporations, which have been merged or consolidated into the larger institutions. Now, for this apparatus that has so soon gone out of use, and for which the larger corporation had no use whatsoever, securities were issued in good faith and bought by the investor, and yet the physical assets, as has been referred to, have disappeared, and when these valuations are made even the closest scrutiny and search will not find anything in the existing operating system that represents these disappeared values.

Now, I think that Mr. Arnold has, as a result of the deep thought which he has given to this subject, and of his experience, touched upon a very important and reasonable method of suggesting they take care of these assets which have disappeared, which cannot any longer be represented as inventory values, in the case of physical valuations of these properties.

It is most important that, as our President has stated in his opening address, which, I believe, should appeal to every engineer, that this is a field in which the engineer should rise to opportunities of wider usefulness. It is astonishing that public opinion should be moulded and shaped on these most important and vital questions relating to our industry by people who have not had the right experience of the business and who have not had information as to these repeated cycles of changes which are reflected in our business conditions, and it is up to us, as engineers, to do our part to shape and mould public opinion, so that not only the public shall have its fair, equitable and just treatment and consideration, but that the public service corporations also shall receive on their part that fair treatment which the public, when it is once correctly informed, will not be slow in awarding to them.

Schuyler S. Wheeler: I have only two points to make.

First: It is evident that depreciation of the property of public service corporations is the important part of the subject as presented, but the titles of the papers are not limited to this. This difficulty would be met if the titles of the papers were conc sidered as amended to read, "Depreciation as Related to *Publi-Service* Electrical Properties," and "The Responsibilities of Electrical Engineers in Making Appraisals of *Public Service* Corporations."

Second: It seems to me it would be much better if all kinds of depreciations of physical property were unified and classified, and a single rate of depreciation was universally adopted for each kind of article making up a property. I refer to the several ways in which depreciation is figured at present as illustrated under "Classes of Depreciation" in Mr. Floy's paper. I think he calls for both "absolute" and "theoretical" depreciation. These various rates of depreciation for the same thing, are intended to cover different circumstances, for example, the fact that on one hand a piece of apparatus may become very old and yet be wholly and fully useful to the owner, and, on the other hand if the apparatus is to be disposed of the value is very small.

Now I think that there is approximately a definite value for each piece of apparatus at different periods in its life; that such value includes actual wearing out and obsolescence and all of the other factors, and I think if we could arrive at some definite way to include all of these factors, and at a rate for each different kind of property, the problem would be very much simplified for us and many arguments would be cut out. I think it proper that in the conduct of every kind of business an amount should be charged each year against the earnings, representing that year's share of the reduction of the value of the property, and whether it be in a lighting company, a street railway, a manufacturing plant, or anything else, such charge should be deducted each year. If the property is considered each year as reduced by that amount the problem becomes quite definite and very much simplified.

E. Leonarz: Mr. Arnold called attention to the fact that a fair interest is allowed. Now, we certainly don't fear that rates would be increased, due to the original rates being too low. We have never heard that rates are being adjusted, when extensions of lines outside of cities have been asked for, but we hear that such rates are being lowered, or that lines are being extended from the previous limits, and the result is simply a higher investment, and sometimes that companies are going to the wall. Who is going to pay for these extensions and betterments? I think that such companies should be allowed increased rates, and that public service commissions should also take into consideration that only a part, and only a very small part, of the capital invested has received what we can call a fair return.

Public service commissions are also apt to take exception to the high rate of interest allowed to certain companies, which from the start, were led to believe that the field which they started in would really be better than it proved to be.

A. H. Ford: The question of reasonable return having been mentioned the speaker raises the question as to whether it is good policy for the controlling body to fix a single rate as a reasonable rate of return. He would answer in the negative; for if the management of a property knows that charges can be increased if this rate of return on the value of the property is not reached and will be reduced by the controlling body if it is exceeded, the incentive for operating the property more efficiently or with greater enterprise, is removed.

A better plan, it seems to the speaker, would be to fix the reasonable rate of return between certain limits as, for example, five and fifteen per cent of the value of the property; giving the controlling body the right to order a reduction of the charges only in case the rate of return is greater than the upper limit and allowing the management to increase charges only in case the rate of return is less than the lower limit.

Specifically; under the present plan there would be no incentive to replace an obsolete piece of machinery which involves a high operating cost by a new machine which would reduce the operating cost and thus allow greater earnings, which would be an invitation to begin action for a reduction of charges; while under the proposed plan this would be advisable. In another instance a reduction of charges might cause such an increase in the business that the earnings would increase but the management would hesitate to reduce charges if it knew that any increase in the rate of return resulting therefrom would be the cause of a further reduction until the rate of return was at the old figure. That this is not a hypothetical case is shown by the action of the Wisconsin Railroad Commission reported in the *Electrical World*, Vol. 57, p. 1599, in the case of the Madison Gas & Electric. Co.

Geo. L. Hoxie: Mr. Floy's paper is a timely one, upon an important subject. It is likely there will be little dissent from most of his conclusions. The table giving the rates of depreciation that have been adopted by various official bodies is particularly valuable, and the quoted extracts from various Court decisions are convenient for reference.

Certain features of the paper however, are likely to develop sharp differences of opinion. I would take exception to the notion of " absolute " and " theoretical " depreciation, and to the idea that " theoretical " depreciation must be provided for only as a part of operating expense, while " absolute " depreciation, for which Mr. Floy indicates quite a different value, is to be used as the basis on which rates are to be fixed, capitalization allowed, etc.

It does not seem that such a division of depreciation into two values, one to be used in one case, and one in another, is at all possible as a practical matter and if it were tried I believe that it would quickly lead to an intolerable situation. In a rate fixing matter for example, the Board, or Commission, fixing the rates would, under Mr. Floy's theory, assign a value to the physical property based upon what he terms "absolute" depreciation, which it seems would usually be very close to the first cost of the apparatus considered, (as in the case covered by the St. Louis decision, so approvingly quoted.) Then the Commission would fix a yearly *rate* of depreciation, and this rate of depreciation would perhaps be more *per annum*, charged to operating expenses, than the *total* "absolute" depreciation.

After rate regulation had gone on for a few years, say 10 years, we should have a fund, paid out of operating expenses, equal to perhaps 50 per cent of the first cost of the plant, and this fund, as would ordinarily be the case, has perhaps been largely expended in extensions and improvements to the plant, (to the extent of keeping its "theoretical" total value constant); but the property of the Company, based on "absolute" depreciation would, if maintained at full operating efficiency still be figured at within a few per cent of its original cost or would be, on this theory, (with a "theoretical" rate of say 5 per cent, nearly 50 per cent more than the first cost of the original plant, at the time when rate regulation started. Yet all of the excess value upon which rates must then be based, has been contributed by the consumer. The consumer has thus paid for the privilege of paying dividends to others on his own payments to them. One can see readily enough that this theory carried out over a term of years would mean rates so high that any Public Service Company should be able constantly to increase its physical property, without any additional capital investment, meanwhile paying full dividends each year on the increased value for that year.

Of course, something of the sort is what has actually gone on in the case of many successful Public Service corporations; but it is precisely such a state of affairs that has brought about rate regulation. Some important Public Service enterprises have mainly been built out of excess earnings. Once built and the excess earnings capitalized, it is impossible for the public to go back, and in effect take away property from stockholders, on a plea that it was paid for by the public out of excess earnings.

If now, we base plant value on one rate of depreciation of plant, and allow operating expenses on a rate of depreciation that is many times higher, we have made no improvement by our rate regulation. On the contrary we have made matters worse, for, under rate regulation, we have eliminated the competition that formerly limited rates, and we have in effect guaranteed rates sufficient to pay dividends on unjust values. The thing cuts both ways. You cannot charge depreciation in your operating expenses unless you lower your estimated plant value by the amount charged to operation for depreciation, less the amount put back into the plant. The total " lessening of worth " of a plant during ten years is the sum of the depreciations for each of the ten years—of course less any money put back into plant. In my opinion, with a new company, starting under rate regulation, and having rates permitting fair payment to capital and the charging of straight line depreciation to operation, the value of the physical plant must, each year, be reduced by precisely the amount of the depreciation fund remaining unexpended at the end of that year. The Company must also be allowed to call any unexpended balance, capital, and to earn dividends upon it, crediting earnings of course with any income the fund may have produced.

As a practical matter the depreciation fund of any large company cannot be made up of a lot of separate accounts each balancing the "lessening of worth" of some one item, but it should be a fund balancing the total lessening of worth of all items together. Also as a practical matter, the depreciation fund would not be held in cash for any great length of time, but should be invested, so as to produce a revenue. Of course the investment may be in any form of property, perhaps in the bonds of other companies, or perhaps in the bonds of the company itself. But the most usual form of investment will doubtless be in ***new plant construction.*** Such investment should yield the greatest possible return, and should provide in the best possible manner for balancing the depreciation of the previously existing plant. If an exactly correct rate of depreciation be determined and so balanced by a fund, used in extraordinary repairs, extensions, new constructions, etc., the physical value of the plant will remain constant (unless new capital be also used in construction).

Since no human measurement can be absolutely exact, care should be taken to see that the rate of depreciation chosen is a little too high rather than a little too low, otherwise the company will in time be wrecked. With a depreciation fund a little too large constantly being put into improvements, the value of the property will constantly appreciate. But the public, in the form of a commission, may very justly step in at this point and prevent any increased capitalization or earnings on account of such increased value; but may say to the Company, " This increased value is not yours, but belongs to the public, since it exists solely because we, in our care not to wrong you, purposely allowed you to collect somewhat too large a depreciation fund."

It is easy to see that under such a financial scheme as here outlined, a corporation's bond and stockholders would become more secure each year as to the safety of their original investments, yet they are not allowed any " unearned increment." There would probably come a time when not merely 75 per cent or 80 per cent but perhaps as much as 100 per cent of any additional funds needed for extensions, could be had from low rate bond issues. The public, on the other hand, would get the benefit of steadily decreasing rates.

A much more difficult situation, and perhaps such a one as Mr. Floy had mainly in mind and attempted to meet by two rates of depreciation, is found where a public service company having handled its business as it pleased for many years, suddenly comes under rate regulation. Such cases are almost the usual ones now. It must be admitted at once that fixed rules are almost impossible. Each separate case is of a corporation whose history is somewhat different from every other one. Some corporations have been conservative, some reckless; some have had good engineering, and some no engineering; some have maintained depreciation funds, some have largely built their properties out of excess earnings, and some have capitalized everything, watered to the limit, made no proper provision for depreciation, and perhaps the promoters have withdrawn with personal fortunes, leaving a lot of deluded stockholders, a run down plant, and a new rate making commission, to be dealt with.

About the only general rule that can be laid down is that each case must be treated with common sense at the start, and that the treatment must look toward the establishment, as quickly as possible, of such conditions of business management as would be enforced at once on a new concern.

There can be no doubt that a "theoretical" rate of depreciation must in every case be charged against operating expenses. Possibly, to begin with, the theory of a lesser "absolute" rate of depreciation might bring out a common sense result in some cases, and *for a limited time*. In my opinion however, there is no case, and there can be no case, where the continued use of two separate rates of depreciation, applied to the same property, over a considerable series of years, will not bring disaster.

The real difficulty in making an appraisal of machinery in use, lies in what is almost the impossibility of correctly estimating the remaining period of life of the machinery, during which it will be of effective service to its original owners. This is a different matter from estimating the useful life of the machinery alone. Many a machine sold second hand, for approximately scrap value, has a long period of useful life ahead. But for its original owners the machine's life ended when it was discarded.

An engineer making an appraisal must not therefore limit himself solely to the physical condition of each machine. The physical condition of property may be the smallest factor of its value. In some way or other, the appraisal must be made to include a deliberate judgment of *value of useful service remaining*, in that situation, or to that company, plus salvage value. To say that an engineer can make such a prediction accurately for any given machine is to say that he can predict not only future advances in the art, but how many years ahead those advances will come. The best that the engineer—or anyone else—can do, is to judge the future by the past. He may say that various classes of machinery have in the past had such and such periods of life. He may increase those periods by an amount that in his judgment it is fair to allow, assuming that future progress will be less rapid owing to greater standardization. He may then apply a depreciation based on age, and years of service remaining, and while method and result may be criticized, both are likely to be more nearly right than any other yet suggested.

Objection comes mostly from a general sense that injustice may be done to innocent stockholders, where application of straight line depreciation would make a drastic reduction in capital, of a sudden, which could not have been anticipated. In such cases the public must share responsibility for not having regulated matters earlier and a commission may reasonably, for a time, allow capital, and earnings, on some sum in excess of actual value as depreciated, and may thereby in effect assess upon the public some part of the loss due to bad financial history, which loss the public and the aforesaid innocent stockholders then share, upon some basis to be determined by the commission.

Conflicting Decisions. The Master's Report in the Consolidated Gas Case, from which Mr. Floy quotes, seems at first to be opposed to the method of estimating depreciation just outlined. As the Master's opinion was sustained by the Supreme Court, it seems a little presumptuous to differ—yet other decisions do not indicate that approval of the Master's Report constitutes a final pronouncement concerning the method that we must follow. The Master approves an estimate "based on a detailed examination of the property as it stands to-day." No one could object to such an estimate if correctly made. Such an estimate would necessarily consider not merely physical condition, but probable length of future service; and it is evident from the Master's opinion that he actually did consider the plant in condition to give service over a long period to come. It must also be noted that while a straight line depreciation is well within the possible limits of accuracy for any case where the length of life is short, in cases where the estimated life is long, as in the Consolidated Gas Case, a moderate rate of interest for the fund makes the annual charge against operating expenses very small. A sum amounting to a few per cent of the first cost, set at interest at the end of half the estimated life might in many cases reproduce the property at the end of its theoretical life. It does not seem possible to get more than a meaningless figure from a computation based on a life of 100 years or more. In Mr. Floy's curves, Plate 1, the annual charge to cover depreciation, at 5 per cent on 100 years of life, is practically nothing. The fund and interest, accumulating even at the end of 10 years, can hardly be read on the curve. In fact any estimated life beyond 60 to 75 years might reasonably be called perpetual life, for no computation, based upon such a life will be within the limits of error introduced by other uncertain factors, not the least of which is the estimated life itself. It seems clear therefore that the opinion in the Consolidated Gas Case by no means tells us not to figure straight line depreciation in the case of an electric lighting or railway plant, having a probable life of less than 20 years. Certainly it does not tell us to figure two kinds of depreciation, one to use for an operating charge, and the other for a capital charge.

Curves of Depreciation. In Fig. 1 of Mr. Floy's paper are given six curves, as illustrating ways in which depreciation actually takes place. Curves 1 and 2, are based on selling values, assuming that the depreciated property is sold for use elsewhere. As the author says, depreciation of a going property should never be figured on the basis of these curves—unless the property depreciated is of less value to the seller than to the buyer, and in that case the property should be considered as scrap, and not included at all in a value of the property on which for instance, rates are to be based. Curves 1 and 2 therefore are not truly such depreciation curves as may be used for going properties. Curve 6 is for property which it is assumed will be kept at close to 100 per cent of operating efficiency until just before the end of its life. It seems that the reasoning given in connection with curve 6, while at first sight plausible, is in fact wholly misleading. Assume, as shown by this curve, that a property gives precisely the same service at the end of the 17th year of its life as at the end of its first year. Also assume, as the curve also assumes, that at the end of its 20th year it has only scrap value. Decided the "fair value" of the property is very different at the end of one year and at the end of 17 years. The property value is due to its *remaining capacity* to serve—not at all to the *momentary character* of its service. Curve 6 cannot even approximately illustrate possible true depreciation. The curve is not really a depreciation curve at all, but is in fact a curve whose ordinates represent operating efficiency, at the end of any given time—quite a different thing.

Curves 3, 4 and 5 are the only curves of Fig. 1 that may fairly be called depreciation curves for an operating property. Mr. Floy calls these, curves of "theoretical" depreciation. It would seem better to call them curves of "actual" or "real" depreciation. The only uncertain point is the length of life. Give the real length of life of the property, and curves 3, 4 and 5 are not at all "theoretical", but very practical and definite.

Interest on Depreciation Fund. Curve No. 4, and the similar curves of Plate 1, show the effect of interest rates, assuming that the gradually growing depreciation fund is kept at compound interest until the life of the property is over, and is then exactly sufficient to replace the property. Curve 3 illustrates what is usually called "straight line depreciation."

There is something to be said on both sides of the question of whether to include interest computations, or to use straight line values. Personally I much prefer the straight line method for all ordinary cases of property having a life not over about 25 years, the objections to including interest figures being:

1. It is not practical, or desirable, to have an actual fund against each piece of property, maintained as an invested fund during the property's life.

2. If the fund be general, against the entire physical property, it will be drawn from, at varying times, and usually invested in plant extensions, none of them specifically replacing any especial part of the old plant, but all together maintaining the total physical property at a constant value.

3. It is difficult, and perhaps impossible, to estimate in advance the probable life of property so closely, that the error will not usually be greater than the difference between straight line, and curved line, depreciation. (For very long lived properties this might not be true.)

4. Rates of interest will not be constant during the life of a property, and will depend largely on whether the fund is kept in bank, used in purchase of bonds, or re-invested in extensions. One method may result in a rate of interest twice as great as another.

5. The straight line method is far simpler.

Even where statistics are so accurate as those of human life, it is found that progress in sanitation, medicine and surgery, together with the strict examinations of the physical condition and family history of applicants, has resulted in an average length of life of insured persons, appreciably greater than indicated by the tables.

It would seem impossible to estimate the average useful life of 1000 similar dynamos with such accuracy as to justify the inclusion of interest. For one thing there may be quite a difference of opinion as to when a dynamo is really "dead". Furthermore the salvage value at the end of the period of life cannot be estimated at the beginning of life. There are other similar uncertainties none of which occur in the problems of a life insurance actuary.

It seems therefore that such account as it may be desirable to take of interest on fund, at least for the depreciation of electrical machinery, might usually best be considered as a lengthening of the life period; using always "straight line" depreciation.

Fifty Per Cent Method. The "fifty per cent method" in certain cases, such as those mentioned by Mr. Floy, is quite a satisfactory one. It implies a relatively short life, or the inclusion of an interest factor. It should be noted that there is nothing theoretical about the depreciation where the fifty per cent method is applicable. Take the case of the incandescent lamps, on customers premises, of a company furnishing free lamp renewals. Some lamps are new, some just ready to be exchanged, and others of all ages between maximum and minimum. No one would maintain that the total value of stock, old and new together, is not close to 50 per cent of the new value. Also it is evident that the renewal of lamps as they become burned out or blackened keeps the whole outstanding stock at about a constant value, making no special additional charge for depreciation necessary, except as lamps may become cheaper due to improvements in manufacture, etc., or as new types may make the old ones less valuable.

The question of when the " fifty per cent method " should be used is one requiring careful judgment. It is interesting to observe that when the Third Avenue Receiver, as Mr. Floy tells us, refuses to provide for depreciation, on the plea that the property has so many elements that all deterioration is simply wear and tear, and to be charged as maintenance, he really applies the " Fifty per cent method " to his entire system, and in effect inventories his property then and there at 50 per cent of its replacement value. If he is correct in his notion as to maintenance, the system may be easily appraised.

Use of Terms. The suggestions made by Mr. Floy on the subject of a more general agreement on terms are very wise. It would seem appropriate for the Institute, through some of its committees, to take up the whole question of terminology in connection with depreciation, and assign very definite meanings to the commonly used terms, and perhaps to coin new words if desirable. Such a committee might well work in connection with committees from the other societies, as all are equally interested.

P. H. Thomas: Mr. Floy has given us a valuable paper on the subject of depreciation and has clearly brought out a number of matters which are at present the subject of wide controversy. There seems to be an endless line of opinions and theories as to what constitutes the logical basis for the disposal of many of the questions arising in assigning depreciation rates in actual cases and more broadly in the matter of the determination of rates and utility investment values. Such matters are good will, promotion expenses, cost of building up a business, insurance, engineering, etc.

Is it not clear, however, as a matter of public welfare, and common sense that there is but one sound and logical rule by which all such questions must be judged, namely, whether under the ruling proposed the capital invested will receive a sufficient return to warrant its leaving other available lines of investment for public utility plants, this being the sort of property now under discussion. The community must have its utility plants developed and extended continually, and while it is under no obligation to contribute in any degree for the benefit of the capitalist, it must make its offer attractive enough to secure takers. It may be and in fact is possible to force a company which is already involved in a particular plant to do things it is inequitable to require and even to make some extensions to save a portion of the investment already made, which cannot be withdrawn, but this policy would in the long run end in stopping all development and furthermore is obnoxious to our sense of justice.

From this point of view it is relatively easy to determine the disposal of many of the disputed questions. Would the particular expenses sought to be added to capital account be necessarily incurred were the plant to be reëstablished *under the original conditions*? The costs of preliminary studies, within reasonable limits, the costs of engineering, insurance, the cost of building up the business, the losses and inadequate profits during the early years, interest charges, and all such expenses are necessary steps in the establishment of such a plant and are a legitimate part of the investment. On the other hand, the cost of mistakes, bad judgment, discounts or profits which are paid to persons or corporations for some reasons other than the necessity of the plant itself would not be legitimate additions to the capitalization. This exception should, however, be noted that a suitable percentage added to actual cost due to mistakes or accidents, etc., should be allowed to the extent actually found in similar undertakings carried out with average good judgment. Promotion expenses should usually be small in public utilities as such systems usually grow from a small size with the development of the community.

On the basis here set forth the cost to reproduce new is not a fair measure of the value of the plant. It should be the cost to reproduce again under exactly the same conditions that existed when the plant was actually developed. But in practice on account of the great difficulty of fairly determining such a cost under the old conditions it is customary to determine the cost new as a guide. Many appraisers in relying mainly on the cost to reproduce new seem to consider that the records and books of the company are so confused and interlaced with legitimate and illegal expenditures that it is hopeless to try to sort them out. This is a dangerous precedent from the point of view of securing fresh capital and suggests the importance of keeping the books so that legitimate expenses can all be shown, with their justification, at a later period, and with enough detail so that suspicion cannot be thrown on the totals.

There is another aspect of these discussions which has not been very clearly stated. In most cases of the determining of depreciation or in rate making, we may either strive to determine what the precedents of the courts state to be the law, leading to the probable immediate holding in any given case, or we may consider what is the ideal or logical or wise or fair determination. While in one sense the precedents of the courts are fixed rules, it is nevertheless true that the decisions must ultimately meet the sense of public fairness and good policy, either through additional legislation or otherwise and that the continual discussion of the ideal, that it may be clear and well recognized, is of the greatest importance to the community. It is gratifying to note that the spirit of intelligent fairness seems to be rapidly spreading, in spite of certain somewhat radical tendencies that appear.

Wm. A. Del Mar: In the summary of his paper, Mr. Floy gives first place to the following feature.

"The necessity of a more general agreement on and uniform use of the terms used in considering and discussing the subject of depreciation, by the engineering profession."

Mr. Floy is to be commended for pressing the importance of this point, for in most of the literature on the subject of depreciation the meaning of the principal terms has to be painfully ascertained from the context. Unfortunately our author, while generously assisting others over the pitfalls of loose phraseology, himself falls into them, dragging the reader into the very trap that he set out to save them from. For example, he defines the word depreciation in two different ways. The first definition is as follows.

"Webster defines 'depreciation' as the act or state of lessening the worth of and in this sense it will be used by the writer. . .".

The second definition which occurs only twenty lines after the first says that "depreciation has been used to mean—

"The annual amount expressed, as a percentage or in dollars that should be laid aside to renew or replace the article in question at the time of its abandonment, plus the annual expense of maintenance of repair expended in removing such part of depreciation as is practicable and good economy. This then includes all classes of 'lessening of worth' and is the application of the term preferred by the writer. . . .".

The first definition says that depreciation is the state of something and the second, that it is an amount that may be expressed in dollars. If both are to be accepted it must follow that "states of something" can be measured in dollars, a point of view that opens up a new era in political economy and the theory of dimensions! I fear, however, that science is not destined to be enriched by such a discovery, as many readers will notice that the second definition is invalidated and rendered useless by the fact that it defines depreciation in terms of itself.

Later in the paper, wear and tear, decrepitude, supersession and obsolescence are defined as classes of depreciation. It is obvious that our author here follows his first definition, but with the result that he tries to measure supersession and obsolescence in dollars, which is impossible because the physical dimensions of these two quantities are indeterminate while that of a dollar, as explained below, is determinate and known. If Mr. Floy had defined depreciation as a lessening of value and then said that supersession, obsolescence, etc., were *causes* (not classes), of depreciation he would have kept out of this confusion.

If carelessness occurs in the definition of depreciation, what shall be said of the following use of the word valuable?

"On the other hand, apparatus that is in use and rendering a service economically, may for the purpose for which it was intended, be as valuable as when originally installed, although its age may be approaching the limit of its life."

Is it possible that our author does not distinguish between "useful" and "valuable", that he uses the latter term to mean the former? Apparently not, for it is obvious from what follows that the confusion is one of ideas and not merely of words. Thus, curves 1, 2 and 6, he says, "may be taken to represent absolute depreciation" by which he means *loss of utility*, while curves 3, 4, and 5 represent "theoretical depreciation" by which he means *loss of value*. The fallacy of Fig. 1 is the attempt to measure utility in dollars which are obviously incapable of measuring anything but value.

Another example of the confusion of the terms value and utility occurs under "Service Value."

"Physical property, honestly and intelligently purchased with a view to its suitableness for the service intended, aside from some hidden defect or untoward accident maintains its original value practically throughout its life, etc."

Does Mr. Floy mean value where he says value, or does he mean utility? This is only one case out of a score, where the meaning is doubtful, and the same criticism applies to many other words.

Leaving the field of corrective criticism and entering that of constructive thought, let us consider a few definitions which are not open to the objections cited above.

The *value* of a commodity or service is the inverse ratio of the amount of that service or commodity, to the amount of another service or commodity which it can be exchanged for. Value is therefore a ratio and according to modern political economists, is proportional to the ratio of two numbers, one of which is the ratio between the demand and supply of a service or commodity at a given place and time, and the other the ratio between the demand and supply of another service or commodity at the same place and time.* Expressed mathematically it is as follows:

$$\text{Value} \propto \frac{\frac{D}{S}}{\frac{d}{s}}$$

where D and d represent demand and S and s represent supply. The physical dimensions of value are therefore undeniably those of a ratio or number.

The magnitude of the ratio appears when an exchange is effected, or proposed and therefore to all intents and purposes is nonexistent without an actual or potential exchange.

Just as an angle is measured by the ratio of its magnitude to the entire circle, so a value is measured by the ratio of its magnitude to the entire sum of exchanges effected in some arbitrary time, say a year. The equation of value and money is as follows:

$$A = D\ V$$

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*Science of Money, Alex. Del Mar.

where A = value of the sum of all the exchanges effected with money, per annum.
D = number of dollars in circulation.
V = number of times per annum that each dollar is used, usually called the velocity of circulation

Expressed in terms of their ultimate physical dimensions

A is a value, which is a number, divided by a time or $\left[\frac{1}{T}\right]$

D is a number represented by [1]

V is a number divided by a time, or $\left[\frac{1}{T}\right]$

Hence our equation checks by dimensions $\left[\frac{1}{T}\right]=\left[1\times\frac{1}{T}\right]$

The time element may be eliminated from the equation by dividing each side by T. Performing this elimination we obtain $a=D\,v$, where v is the number of times each dollar is used while exchanges to the value of a dollars are effected with money. Hence an exchange which involves $1/n$ of the total value of all exchanges will require $1/n$th of $D\,v$, which therefore is the measure of value involved in that exchange. The physical dimensions of $D\,v$ are the same as those of D, that is to say a number. All this is very simple, but the number of people who write on depreciation and don't know it, is legion.

Value being a number and its unit also a number, the physical dimensions of *money* are those of a number, and do not involve time, mass or length. Hence money cannot measure anything that involves time, mass or length. Now utility is not a ratio or number; it is a complex quantity incapable of mathematical expression and having no unit. A gold nugget might have been useful to Robinson Crusoe, but its value in dollars on Crusoe's island was certainly zero. Utility not being reducible to the physical dimensions of money it is as futile to try to measure utility in dollars as to measure distance in pound weights. Yet by disguising loss of utility under the name of " absolute depreciation " Mr. Floy attempts to perform this impossible feat. By substituting " percentage of original utility " for the word " dollars," in his Fig. 1 our author would have made his meaning clear without using absurd expressions, although an attempt to measure utility or any other quantity having no unit is apparently vain.

This excursion in to the realm of elementary monetary science seems necessary because depreciation relates to a change in value expressed in money and this change cannot be clearly understood without a clear conception of what it is that changes.

Another element in the conception of depreciation, is *deterioration*, which may be defined as any change in a property due to wear and tear or the ravages of the elements, which tends to impair either its usefulness or its life. Akin to deterioration, is *loss of useful association*, which may be defined as any change in the associations of a property, which tends to impair its usefulness or life. Finally before coming to depreciation itself, it is necessary to define *obsolescence* as loss of commercial utility in any property, due either to the advent of superior substitutes or to its own inadequacy to meet new conditions.

Depreciation may be defined as a lessening of value due to deterioration, loss of useful association or obsolescence.

Deterioration can be approximately predetermined from the results of experience, while loss of useful association and obsolescence are of a more speculative character and less amenable to computation. While, therefore, it is possible to estimate to some degree of accuracy, how much it will cost to overcome deterioration, it is possible only to bet or insure against obsolescence and loss of useful association.

The expression *replacement cost* means the cost of replacing an existing property by a new one either identical with it or possessing equal utility.

On account of deterioration, it is necessary to make replacements and repairs. Those replacements and repairs which occur frequently, or which severally cost a small portion of the whole replacement cost, should be made when required, paid for out of the annual earnings and charged to direct operating expenses. Such charges are called *maintenance* charges.

Replacements which occur infrequently and which cost an important proportion of the whole replacement cost, cannot be paid for out of the annual earnings without causing exaggerated operating charges in given years, unless a proper sum is set aside each year to provide in advance for the impending replacements. Such a sum is called a *depreciation charge* and the accumulated fund made up of these annual sums and the interest thereon, if invested, is called a *depreciation fund*. Considering only those elements of a property whose depreciation is offset by a depreciation fund, we may state as a general principle, that the ideal condition is that the depreciated value plus the depreciation fund should at all times be equal to the replacement cost.

This completes a set of definitions which are proposed in place of the corresponding ones used in the paper under discussion.

Mr. Floy's paper contains a great deal that is valuable upon this important subject and it is to be regretted that the presentation of such an elaborate research should be disappointing in the very feature that its author apparently set out to perfect, namely the uniform and correct use of the terms used in the discussion of depreciation.

F. W. Harris: Mr. Floy says that by the second plan consumer saves 25 per cent. I do not think this is so broadly considered and I cannot see that the consumer saves anything with prevailing interest rates considered. What happens is that each year the corporation borrows an additional $100,000 and charges the interest to the consumer. This is fair to the consumer and if the rate of interest is a fair one is financially equal to paying it. This is readily seen if the consumers are considered as each year putting aside $100,000 at 6 per cent and each year paying the interest therefrom plus $60,000 to the corporation. At the end of 50 years the consumers will have a sinking fund of $5,000,000 and the corporation will have a debt of $5,000,000.

While, however, such a course as outlined in the first plan is fair to the consumer and practically equivalent to the second plan it is suicidal to the corporation due to the difficulty of properly securing this loaned depreciation. The corporation is in reality loaning its customers $100,000 a year without security. Such a course would be the height of folly but there are many corporations today which are on a smaller scale persisting in just such a course.

Mr. Floy's paper is aimed at such and is to be commended but his statement regarding consumer's position does not seem to me sound and as this is an important subject I have ventured to comment as above.

Horatio A. Foster: Mr. Floy has covered quite fully in his paper about all the ground work of the subject but I wish to add to his definition of the word depreciation the following: theoretically, depreciation of an object is that deterioration in its value that cannot be made good by repairs nor can it be made good in any way except by full replacement or renewal. From a bookkeeping standpoint we must get away from the ordinary conception of depreciation that it is just wear and tear because in making the changes on the books the wear and tear and what is termed deferred maintenance are all chargeable in operating expenses. In evaluating a property, however, all these conditions of wear and tear and deferred maintenance are considered with the depreciation the definition of which thus becomes, *any lessening of worth at the moment of appraisal.*

With the possibility of repeating I will try to add somewhat to the discussion. Every piece of physical property begins to wear out or deteriorate the minute it is started in operation. To be sure in many cases this is very slow, in very many cases it is not only slow but if there were no obsolescence or inadequacy it would probably give good service for many years. But as it continues to wear out, and as repairs are continually made in the endeavor to keep the property up as near its original value as possible, it is probable that the average of the lack of repairs on a whole property would approximate 15 per cent or if the property were maintained in very high class condition the average of this lack of repairs might be 10 per cent. It is utterly impossible, however, that taken at any moment, the value of the whole property could be 100 per cent of its original cost. I am speaking now, of course, of the original property only and not additions thereto. Therefore, in order that the capital may be maintained at its full value, it will be necessary to have accumulated a surplus or depreciation fund, or renewal fund, covering this 15 per cent, or the capital will be reduced in value just that amount. There is another method which Mr. Floy has touched upon but which I think deserves a little larger notice and that is what he calls the "fifty per cent method" of depreciation. This is only applicable to such large numbers of items of the same kind or nature as depreciate in common and as they wear together through a cycle of repairs, get into one general average condition, for it can be mathematically proven that when a number of articles such as a number of street car motors have all been in the shop for putting into thoroughly good order, the value of these motors new may be decreased by one-half of the total cost of the total repair on a motor; that is, the value of each one of the lot will be first, the total value of that portion of the motor which can not be depreciated, or that portion we might say which is always worth scrap value, or may be said to be worth a certain arbitrary value, say 25 per cent, of the cost new, plus one-half of the cost of the total repair to the motor; that is, the cost of repairs to everything that can be repaired.

Speaking electrically, the question of depreciation in connection with arc lamps, meters, and pole transformers should be given thorough consideration in any valuation, for the reason that these smaller items change in type so fast, wear out so soon, and are changed around so much that they are of no value at the end of 10 years, and often in much less time. In fact, I believe the larger companies depreciate them fully 1/10 per annum, for the reason that they go out of style so soon and that new forms are produced to replace them which are so superior that no excuse can be found for holding over the old ones.

It would be interesting to learn how Mr. Floy would treat the property of the Massachusetts street railways some of the values of which have been entirely wiped out by re-organization. For example, take the property of the Springfield street car system which was a good type of horse railway, and when it was electrified nearly the entire property then existing had to be abandoned, the horses sold, the car houses rebuilt or removed, the stables destroyed or used for storehouses, the track entirely reconstructed, and to this cost was added that of the powerhouses, new car houses and new cars, all of the old ones being of no use under the new construction.

If an appraisal of the property of the Springfield Street railways were to be made at this moment the only values found would be those of the electrified property and nothing would be found of the original possessions covered by the first capitalization except the land. The question is, what has become of this original capital, and still further, what has become of it on the books of the company, or how has it been treated by the Massachusetts Railway Commission? It is the writer's view that an amortization fund should have been established to gradually wipe out the original capital, or perhaps better say, the cost of the original road.

As a matter of fact, we are all merely guessing at depreciation and its extent as no electrical apparatus has yet been installed for a time long enough to determine its actual life. I think I am safe in saying that no one in this room has ever seen a worn out corliss engine and it was the writer's pleasure recently to have seen the first three-phase dynamo installed; that at Redlands, Cal., which was put in place in 1895, I believe, and is still doing most excellent duty.

J. G. Hirsch: Probably no discussion is of more general interest to the engineering profession than one covering some phase of what might be styled engineering finance or accounting, such as that by Mr. Floy. The ultimate analysis in most engineering undertakings is in dollars and cents, and the weakness of engineers on cost and its analysis is an old story. The advent of Public Service Commissions and the necessity for satisfactory, detailed discussion of the financial aspects of especially the power projects of today must force the engineer to the fore on the subject, due to the fact that he has the pre-requisite understanding of the technical considerations.

In making estimates, I feel certain that it has been the custom of many engineers to give little more consideration to provision for, and operation of, depreciation, than to setting down a certain rate for the interest on the investment as a fixed charge.

The application of the terms depreciation, obsolescence and amortization has been bewildering to me. This much can be said, that they all *operate* as a charge on the operation of the enterprise. The acceptance of a single term, depreciation, and its proper definition, reduction of worth, will eliminate confusion. The term should not be confounded with the annual depreciation "charge", which is made to provide for the "loss of worth", or the "depreciation fund" or "depreciation reserve fund" (the latter to distinguish from a sinking fund)which has accumulated up to a given time in the life of an item. In my opinion it is not wise to generally consider a depreciation fund as related to a sinking fund in the sense of a provision for contingencies. The provision of a sinking fund proper has its own field. In this connection I gather that Mr. Floy would combine provision for depreciation and the cost of maintenance and repairs in one item of charge. I regard a depreciation charge as one of fixed annual amount, based on the assumed useful life of the property; maintenance and repairs are quite dependent on the particular service required of the plant, and the attention given in its proper care. The amount of charges for maintenance and repairs is then dependent on the operation of a plant or property in much the same way as the care of firing a boiler, for instance, will determine the fuel cost. Then is not a charge for maintenance and repairs properly an operating charge? It is admitted that in the case of an extended system with numbers of similar items, the distinction between maintenance and repair charges, and depreciation charges, may be considered of such minor importance as to be dropped in accounting, but the principle remains, for the extended system is quite the exception to the rule.

While I agree with Mr. Floy that the application to be made of figures for depreciation charges should be known when the figures are decided upon, I feel that the underlying principles which determine the figures are definitely fixed except in very special cases. In this connection he designates certain reductions of worth as theoretical and others as absolute. If the value of a plant is to be estimated for any purpose it is only fair to consider its remaining useful life in fixing the value. The value of a property is, therefore, directly dependent upon its remaining useful life at the time. It seems to me that this proposition is no different from the purchase of a horse on the basis of age. From the financial standpoint, with proper management and accounting, the sum of plant value and the depreciation fund, at a given time, equals original investment. A going plant maintains practically constant profit earning power throughout its useful life, about as indicated by Curve 6 of the paper, dropping off slightly during the period of life owing to loss of efficiency and deterioration which cannot be removed by repair. Also, an abstract lot of plant equipment drops off in value immediately after purchase, about as shown by Curves 1 and 2 of the paper. Now as plants or other engineering works are built with the intention of their being operating business propositions over the period of their useful life at least, and as the *remaining total earning power* becomes less year by year in direct proportion to the life remaining, therefore, the value of the property must decrease uniformly throughout the period. The facts remain even though no depreciation fund is maintained, where a faulty business management fails to make provision for keeping the investment unimpaired, as in the case of many municipalities which, once the lighting or water works plant is in operation, provide appropriations sufficient to cover running expenses only, interest on the investment being usually paid from a general fund, and depreciation not at all provided for until demanded by the maturity of the bonds. When estimating the cost of production or operating expense in reporting upon a proposition, or when investigating an operating plant, charges for depreciation are uniformly distributed over the period assumed as limiting its useful life, in order that capital may be returned at the same rate that remaining total earning power decreases.

The above considerations argue for *uniform* reduction in worth as the actual depreciation of a going plant, (uniform depreciation charges, such as indicated by Curve 3, or the straight line method) and as the practical and logical method of providing a depreciation fund, as against Mr. Floy's designation theoretical to this method.

The method indicated by Curve 4 is a legitimate distortion of Curve 3, developed by the financial consideration that all idle funds should be put out at interest. A method such as that represented by Curve 5 is a distortion of the real principles of providing for depreciation, developed for special considerations in accounting or business administration.

In considering obsolescence, any difference in value of an item, at the time of its replacement, and its salvage or scrap value, should be charged as capital added to the investment in new equipment replacing the old. If the replacement is not a good investment when burdened with this charge, it is not justified. This point is clearly expounded in a paper on industrial power costs by M. O. Jenkins of the New York Edison Company in the June 20 issue of *Power*.

I am of the opinion that any figures which might be collected for the life of plants or apparatus would be very unreliable unless accompanied by statements of the economy of the apparatus and the cost of maintenance at the time of replacement. Deferred maintenance will greatly shorten, and extended maintenance and repair will considerably lengthen the life of property and equipment. It has been my experience that industrial concerns and municipalities which do not regularly maintain technical supervision do not rightly appreciate the propriety of alterations and replacements to increase economy and better service; as long as a property runs without failure it is satisfactory, even long after its useful life has expired, as evidenced by decreased efficiency and excessive maintenance charges.

I suggest that it would be most valuable to standardize averages for economical and useful lives of various equipments and structures as indicated by the judgment of engineers of broad experience, through coöperative work by the three National Engineering Societies.

Alten S. Miller: I feel constrained to discuss Mr. Floy's paper briefly for the purpose of accentuating a few of the many good points, and for the purpose of going on record as differing from the author in certain other points. There are many important truths found in the paper they should be carefully studied and understood by every engineer who undertakes to estimate the reproduction cost and the rate of accruing depreciation of any piece of property.

Under Development Expenses, etc., it is stated: "Any one of these terms is generally used to include certain expenses, which, while a necessary part of the complete cost of a going property, are not costs inherently a part of the construction of the physical property, as such."

This statement is somewhat ambiguous. It is well known to every engineer and investor that the plant cannot be built and the property put on an earning basis without these expenses. Such being the case, they are an essential part of the cost.

In view of the general lack of understanding of this subject, it would be well if engineers would always include the overhead charges in making statements of cost, and make a special note if they are not so included.

Under Good Will Mr. Floy states: "A monopoly, as is generally admitted, has no good will which can be evaluated." In the first place, no gas or electric light company is a monopoly. As a rule they are under different managements so that the customer may always use gas or electricity for light or power, assuming that there are no competing gas or electric companies in the territory. In addition, illuminating oil, gasolene and private power plants provide efficient sources of light and power which are sufficient to make people independent and to prevent any one company from securing a monopoly. This being the case, anyone who has managed a large gas or electric property knows that there is such a thing as Good Will and that good will has a very great value.

Mr. Floy criticizes the action of many companies in charging to capital account replacements due to obsolescence.

An examination of the electric light and street railway properties of the larger cities of the world, shows that the property has depreciated so rapidly through obsolescence that few of the companies have earned their interest and depreciation. A quotation is given from the opinion of Justice Brewer, delivered in 1904, as follows: "It is not always reasonable to cast the entire burden of the depreciation on those who have invested their money in railroads." Under many conditions the capitalizing of property that replaces other property which has become obsolete is not only not an error but is eminently proper from the point of view of the investor and the public.

Obsolescence is shown in one of two ways: Either the service is not abreast of the times and the demand, or the operating expenses are too high. Assuming that either condition has been produced by inventions subsequent to the installation of the plant and that the earnings have not been adequate to permit the investment to be written off, it is to the advantage both of the investor and the public to discard part or all of the old plant and capitalize the replacements. The public thus has increased facilities for which it is proper that the company should be compensated; or economies are realized, the advantage of which may be enjoyed by both the investor and the public.

The table given assumes that the property is profitable from the beginning, and that the company can afford to set aside $160,000 each year for interest and depreciation. In view of the fact that few if any of the public service corporations are so fortunate as to earn interest and depreciation during the first years of operation, the real course to be followed in justice to the investor and the public lies between the two plans shown in the table. The depreciation as well as other losses in the early years should be capitalized until the property is earning all expenses including depreciation and an adequate return on the investment.

The author states: "if no depreciation fund is set up, nothing can be included in the cost of operation as necessary to provide for depreciation."

This is partly covered by my statement in the last paragraph. If a company is not earning enough to take care of its depreciation, it is, nevertheless entitled to take the accruing depreciation as a part of its cost of service in any question of rate regulation. A company is warranted in paying interest on its bonds and floating indebtedness before providing for depreciation, and in some cases it is wise to pay dividends on stock in order that additional amounts of money may be raised to develop the property, although if the full amount of depreciation were provided for, such dividends would not be earned. These questions must be settled by the managers of each property and cannot be governed by any general rules.

The author makes the statement: " From the cost should then be deducted this absolute depreciation in order to obtain the present real or service value of the property."

In determining depreciation, is it not safer to estimate the amount that will be required to put the apparatus into a condition that is practically as good as new and call that amount " depreciation " rather than to decide that the machinery is worth say 50, 60 or 70 per cent of its original cost, and to call the difference between one of those figures and the original cost the depreciation? The former is the usual process followed.

The 50 per cent method quoted in the paper is so seldom applicable that it seems hardly proper to quote it as a method having any merit. If there is a piece of property that is not growing and the maintenance of which is uniform from year to year, it is a curiosity. Certainly this method would not be applicable to a growing property or to a case wherein the methods of construction are improving as replacements are made. It is not applicable therefore to the poles, cross-arms and braces of an electric company.

Inasmuch as small transformers, meters and arc lamps have been replaced largely through obsolescence, this rule is not applicable to them. In the case of boilers it may be found that a certain percentage of tubes are replaced each year, but it will be found on inspection that a large portion or all of these tubes will be on the first and second rows, numbered from the bottom. The tubes above this may be 100 per cent efficient, and it would be a serious error therefore, to say that the tubes as a whole are only 50 per cent efficient.

In the case of a gas company the amount spent for maintenance of mains and services might be the same each year, but the depreciation will be found on examination to be due to some local condition, and a large part of the work of maintenance will be done in a few localities. The rest of the pipe system will be in condition as good as new or 100 per cent. Under these conditions it would be grossly improper to say that the distributing system as a whole is only 50 per cent efficient. On the whole it is highly improbable that there is a single case anywhere in which such a method would be properly applicable.

It is stated: " While usually preferable there exists no necessary reason for always writing off certain costs such as engineering, incidentals, etc., at the rate at which the physical property of which they are an inherent part, is depreciated."

It is somewhat difficult to understand exactly what is meant by this paragraph. Replacements usually require engineering and when completed the cost will usually be found to contain many incidentals. In other words, these items are elements of the cost of replacements as well as of the original construction, and to this extent allowance should be made for their depreciation at the same rate as allowance is made for the depreciation of the other values of the inventory property. Such replacements will not affect the design of the property as a whole, and to this extent it is not necessary to depreciate the general engineering and incidental expenses.

In conclusion I will summarize briefly my opinion on the points in which I disagree with Mr. Floy.

Development expenses, intangible or overhead values, are an essential part of the cost of construction of physical property and should be included as such.

Electric light and power properties do not have monopolies, but may have " good will " which latter has a very real value.

It is proper in many cases where corporation earnings have not been sufficient to maintain the property, to capitalize replacements.

If the earnings of a corporation are not sufficient to set up a depreciation fund, it is nevertheless proper for purposes of rate making to include a fair estimated cost of depreciation.

The easiest and safest method of determining depreciation is by estimating the cost of putting the property in a condition substantially as good as new.

The 50 per cent method of estimating depreciation requires so many qualifications and has such a narrow application as to make it very unsafe.

The engineering costs, incidentals, etc., that would probably be involved in connection with replacements should be written off with the physical property in connection with which the expenses have been incurred.

Frank F. Fowle: Mr. Floy's paper on depreciation is notable for its careful analytical treatment of a subject that seems in danger of becoming hackneyed, but which, as he points out, needs more extensive illumination than it has yet received. An examination of the literature on the subject reveals a great mass of material which treats of life tables and associated matters, but little which is specific on the side of theoretical analysis.

The term depreciation is a generic one, meaning the " act of lessening or crying down of price or value," or " the falling of value; reduction of worth." The broad term has been loosely employed in a great many instances with different specific meanings. There is thus great need, as Mr. Floy emphasizes, of careful qualification and definition; and in order to promote mutual understanding among engineers, lawyers, economists and accountants there ought to be established by common consent, a comprehensive and authoritative nomenclature.

In view of the great importance of the subject it is suggested that a special committee of the Institute might be appointed to formulate definitions and stimulate discussion of those phases of the matter which need it; or the Electric Lighting Committee might carry out such a program.

The common confusion between maintenance and depreciation arises, fundamentally, because there has never been devised or applied a thoroughly scientific system of depreciation accounting. It doesn't seem to me that the plan of lumping maintenance and depreciation helps the case any, because there are so many maintenance expenses that have nothing to do with depreciation and are not related in any way to the life of the plant.

In the strictest view of the matter any renewal, however trivial, ought to be charged to depreciation, but in practice it is difficult to do this and as a rule only heavy or important replacements go to depreciation. For example a life of twenty years might be assigned to a certain Corliss engine and it might turn out to be the actual life, but during that time various minor parts would wear out and be replaced, perhaps several times, and the cost charged to maintenance. The problem is to determine how far we ought to go in subdividing a property into its elements or component parts, in classifying renewals as depreciation or maintenance. Two very important purposes of a depreciation fund are to maintain undiminished assets behind the stock and bonds, as the plant wears and depreciates, and secondly to maintain an even annual charge against revenues to take care of replacements and renewals. Other purposes can be mentioned, but these are fundamental. If they are substantially met there can be no argument except over questions of a more purely technical nature.

But this involves the vital question of how property depreciates, or how fast and in what manner it passes from its value new to its scrap or salvage value, when the life is assumed or known. This question Mr. Floy discusses under the head of "absolute" and "theoretical" depreciation. The absolute depreciation of public utility property which forms part of a going concern he defines as curve No. 6 in Fig. 1 of the paper, while the theoretical depreciation might be one of the curves No. 3, No. 4 or No. 5.

There is here a marked difference between two definitions of present value, taken at any time during useful life. The theory represented by curve No. 6 is given in the paper and in substance amounts to this:—that a property which is maintained at approximately full efficiency, without unreasonable expense, throughout its useful life, is substantially worth its cost new, or original cost, up to or very closely approaching the time of its abandonment. That is to say, it is able every day to render the same service and do the same work at undiminished efficiency. Or in other words, present value is measured by a state of readiness to serve or ability to give immediate service, without regard for the future time during which that service can be sustained. On this theory there is very little if any depreciation on a property which is reasonably well maintained.

But is this a correct economic view? We must go back to the definition of value and examine its elements, in order to arrive at any conclusion. The economic definition of value is power in exchange; utility or usefulness is one of the important elements and always present, although it does not, alone, establish value. Ely classifies the elements of value as follows.

$$\text{Value}\begin{cases}\text{Elementary, as in raw materials.}\\ \text{Form, as in manufactured products.}\\ \left.\begin{array}{l}\text{Time}\\ \text{Place}\end{array}\right\}\text{created in retail trade.}\end{cases}$$

In the case of a going public utility, whose business may be assumed to exist through the future years indefinitely, the element of *usefulness*, in its relation to plant value, seems to be most important. For example, such a concern could afford to pay twice as much for a generator (of a given size) which would last 30 years as it could for one which would last 15 years, assuming equal efficiency and maintenance cost. Or again, if the generator which had a 30-year life were 15 years old and in a normal condition of maintenance, the company could afford to pay as much for it as for the new generator which had a 15-year life.

Stating this principle in more general terms, the total usefulness is as much an element of value as immediate usefulness. A state of readiness to serve, without regard for the ability to render prolonged service, is not then the full measure of value; it is naturally an element of value and must be present, but after that it is remaining years of useful life which determine the plant value in a going public utility.

I have never been able to find a sound economic argument for such a theory of present value as that corresponding to curve No. 6 of Fig. 1. Total usefulness seems to me to be the great controlling element, and as that usefulness expires progressively with the rendering of service day by day, so it seems to me the value must expire also.

B. E. Sunny: Every paragraph in Mr. Byllesby's splendid paper is worthy of special notice and comment, but there are two paragraphs of paramount importance.

The first one is with reference to State Commissions.

Originally the idea of State Commissions met with great opposition among the utility companies, for the reason that they had been accustomed to dealing with the State and local municipal authorities, and they did not know whether they would be dealt with fairly by the new body or not.

The splendid record made by the Wisconsin and other Commissions has almost entirely changed the opinion of the public and the utility people with respect to the value of Commissions, and there are few now who do not endorse the State Commission idea of municipal management.

One thing that makes it possible for the State Commissions to deal intelligently and fairly with utility companies is that they are far removed from active politics.

In the City of Chicago, the handling of telephone and gas rates by the City Council during the past two years, during which time nothing has been accomplished, has been seriously interfered with by political considerations.

As a matter of fact, the utility companies as a rule have nothing to fear from either State or City regulation, or by Commissions, inasmuch as that perhaps not more than 5 per cent of the total number are earning in excess of operating expenses a proper charge to depreciation and a fair return on the investment.

Most utility companies are for the time being content if they are able to pay 7 or 8 per cent dividends, but they have either wholly or partially overlooked depreciation and obsolescence, and are making little provision for either.

As a matter of fact, the State Commissions, made up of intelligent experienced business men and engineers, are needed for the aid and guidance in the commercial management of utility companies quite as much as they are needed to protect the public from either bad service or extortion.

The other point in Mr. Byllesby's paper is to the effect that estimates covering new construction are usually too low, and the cost of the work runs all the way from 10 per cent to 100 per cent in excess thereof. This is of course within the experience of every one engaged in construction work.

The suggestion is pertinent that in appraising plants the same percentage of error ought to be taken into account.

In a recent letting in Chicago for caissons for a new office building, six bids ran from $140,000 to $203,000 or a difference of 30 per cent.

In the building of the Sanitary District Canal, some years ago, the work was cut up into sections, and let to a dozen or more contractors. All but one of the contractors failed.

We may or may not know how the contractor comes out on the caissons at $140,000, and we may or may not know how great a loss most of the contractors made on the Sanitary District work. We are likely however to be influenced by, and to make use of corresponding figures when they are applicable for the purpose of appraising work, with the result that a serious injustice is done.

Indeed, I regard it as unsafe to permit one individual or firm employed by the municipality, to appraise a utility property for rate making purposes. I think that in such cases, the utility company should be allowed to have an appraiser to represent its interest, and before the work is begun, the two appraisers should select an umpire to settle the differences which will inevitably arise. It is only in this way that the error to which Mr. Byllesby refers can be at least partially guarded against.

The paper by Mr. Floy is one of the best contributions to the subject of depreciation that I have seen. It brings us down to date on a vital item in the handling of a public utility.

It is significant that Mr. Floy makes no argument with reference to the existence of depreciation. This indicates progress. A dozen or fifteen years ago, there were many who did not believe that there was such a thing as depreciation. Now it is generally recognized. Even today however, depreciation has not taken its proper place in the utility accounting. In good times, depreciation receives liberal treatment out of the satisfactory earnings, while in bad times, when the earnings are scant, it is forgotten. This at least is true of the utility companies, of which as I said above, there are few that are really making any profit where proper charge to depreciation is included.

I am rather in hopes it will not be very long before the practice will become general of including a charge to depreciation with the same regularity and care that we charge to operating expense, interest and dividends, and have the fluctuation with reference to good times and bad reflected in the surplus account.

Halbert P. Gillette: Mr. Floy has presented an interesting discussion of the very important subject of depreciation, particularly from the viewpoint of the appraising engineer. Not only because the author of this paper has mentioned the writers' name in connection with the application of plant mortality tables, but because the writer may be able to add some information on the general subject of depreciation, does the writer offer a discussion of a paper read before a society in which he is not a member.

To begin with, the writer does not use the term depreciation in the sense it is used by the author. The author's use of the term makes it include both the cost of current repairs of parts of each plant unit and entire renewals of whole plant units. The writer uses depreciation to denote the cost of renewal of whole plant units only, and this, he believes, is the sense in which the term is now used by nearly all public service and railway commissions that have had to do with many appraisals of public utilities. Due to the fact that there is still no entire uniformity of practice in the use of the term depreciation, it seems desirable either to adopt the present rather general practice of using it to mean cost of renewals of plant units, or else to adopt the word amortization in its place.

A plant unit is a structure or machine which, for accounting or appraisal purposes, is regarded as a unit; as, a building, a car, a boiler, a railway cross-tie, etc.

The author proposes the expression "theoretical depreciation" to denote the cost of renewals of plant units, but the expression is too cumbersome for convenience in use.

In the second edition of his "Handbook of Cost Data," the writer called attention to the great desideratum of uniformity of practice among engineers in the use of the word depreciation. He also pointed out that while the renewal of entire plant units does not differ in principle from the renewal of parts of the same units, it is desirable to record the costs separately. Thus, the repairs of a locomotive may average 18 per cent of its first cost per annum, while the renewals of entire locomotives may average 4 per cent. The 18 per cent is a repair item, while the 4 per cent is a depreciation item, and the sum of the two, 22 per cent is the total cost of maintenance. Many engineers have made serious blunders in estimating the cost of maintenance by using published depreciation percentages under the mistaken idea that they included current repairs as well as renewals. In fact, engineering literature is replete with examples of just such blunders.

Shall depreciation be deducted from the cost of reproduction new to obtain a plant value that shall be used as a basis for rate making? This is an ever recurring question, and one that grows daily in importance. The writer's own answer has been that depreciation shall be deducted from the new value, but that it must usually be added on again in the form of development expense. The writer uses the term development expense in a sense different from that used by the author of this paper. The writer's definition is:

Development expense is the accumulated deficit in fair return, from the start of operation of a plant until a fair return begins to be earned.

There are some appraising engineers who call this the "going value" instead of development expense, but the term "going value" means so many different things to different men that it is not a desirable term to use.

As an example of the method of calculating development expense, Tables I and II will serve. Table I is based on the assumption that no depreciation has occurred. Table II is based on the assumption that there has been depreciation.

Table I gives an example of a plant assumed to cost $100,000 and to begin operating January 1, 1900. For the sake of simplicity it is assumed that there have been no additions to the original plant. To begin with, assume that there has been no depreciation, and assume that 8 per cent is a "fair return". Then we have the results shown in Table I.

The deficits, column (5) of each year are the development expense of that year, and the total development expense is $5,144, so that at the end of the development period, December 31, 1904, the total value of the property is the cost of the plant, $100,000, plus the development expense, $5,144, or a total of $105,144.

TABLE I

(1) Year	(2) Value Jan. 1	(3) Fair return at 8%	(4) Net earnings from operation	(5) Deficit	(6) Value Dec. 31
1900	$100,000	$8,000	$6,000	$2,000	$102,000
1901	102,000	8,160	6,500	1,660	103,660
1902	103,660	8,293	7,200	1,093	104,753
1903	104,753	8,380	8,000	380	105,133
1904	105,133	8,411	8,400	11	105,144
				$5,144	

Now let us assume that there has been an actual depreciation of $15,000 in the plant value, as disclosed by an appraisal. Then from the actual net earnings should be subtracted such a sum annually as to provide (at 8 per cent fair return) an amount equal to $15,000 at the end of the year 1904. This would be $2,556 deducted annually from the net earnings shown on the books. Table II gives the result of the calculation on this basis.

TABLE II

(1) Year	(2) Value Jan. 1	(3) Fair return at 8%	(4) Net earnings	(5) Sinking fund	(6) Deficit	(7) Value Dec. 31
1900	$100,000	$8,000	$6,000	$2,556	$4,556	$104,556
1901	104,556	8,364	6,500	2,556	4,420	108,976
1902	108,976	8,718	7,200	2,556	4,074	113,050
1903	113,050	9,044	8,000	2,556	3,600	116,650
1904	116,650	9,333	8,400	2,556	3,489	120,139
Total					$20,139	

Table II shows that the total deficit, or development expense, is $20,139 based on the assumption of depreciation, which if added to the depreciated value of $85,000 gives a total of $105,139

Contrasting the results of the methods derived from Tables I and II, we have:

	Table I	Table II
Plant value	$100,000 (new)	$ 85,000 (depreciated)
Development expense	5,144	20,139
Total value	$105,144	$105,139

Had the calculations been carried out to one or more decimal places, the final results would have been identical. We see from this illustration that the development expense calculated on the assumption that the plant has depreciated exceeds the development expense calculated on the assumption of no depreciation, and that this excess is precisely equal to the amount of the depreciation that has occurred during the development period.

There is very much more to the subject of development expense than is likely to occur to one who has not applied it in many cases, but it would lead to such a digression from the subject of depreciation that the writer can not touch upon it further than to point out how it serves to solve the problem of giving justice to a public service corporation that has not provided a sinking fund with which to wipe out the depreciation that an appraisal may show.

Rarely has any large corporation, public or private, provided a depreciation fund with which to recover any considerable part of the loss in plant value due to depreciation. What rational appraising engineer or public service commissioner would contend that a sinking fund should have been established to provide for the loss of value of cross-ties in a railway track? Cross-ties in a track, if properly maintained, ultimately attain an average value of about 50 per cent of their cost new; but who will urge that a sinking fund should be established to provide for a 50 per cent lost value, when the " service value " of the ties is as great at any time as on the day they were first laid? Obviously no one would so contend, unless it were proposed to sell the railway as one would sell a second hand machine, which is a thing that neither the railway owner nor the public contemplates. What holds true of cross-ties holds true of many other plant units. In any event, the writer's method of calculating development expense (as indicated in Tables I and II) shows clearly that if the public intends to be just in its treatment of public service corporations, it must either regard the plant as being worth its actual new cost, or it must permit the corporation to revise its old operating accounts, from the day the plant began operation, so as to include an annual allowance for depreciation, which shall fully cover the past depreciation disclosed by a present day appraisal. This is but common justice, and, when such justice is measured out, it results inevitably in an increase of the development expense by an amount equal to the depreciation, as above shown.

The writer may add that he believes there is a startling surprise in store for the public—a public that has been woefully misled by recent articles in popular magazines as to the extortionate profits made by railways and other public utility corporations. The writer's appraisal of the railways of Washington made it clear that in that state the railways were not robbing the people, and were, in fact, averaging a return that no merchant, manufacturer, or farmer would be contented with.

The writer has recently been engaged on the appraisals of five street railway and interurban electric railway systems, not one of which shows a return on the investment that would satisfy the business men of the communities in which they exist; in fact, the accumulated deficit in fair return, assuming as low as 7 per cent for a fair return rate, has been more than 40 per cent of the aggregate cost of the physical property of these electric railway plants, in spite of the fact that the plants (with one exception) have been long established and are in growing communities. In other words, the development expense of these five electric railway systems has been more than 40 per cent of their first cost, and is not ended yet. Moreover—and this is a matter of extreme importance—this 40 per cent development expense is calculated on the assumption that there has been no depreciation; but, with an adjustment of the accounting records to include depreciation (amortization) as a part of the operating expense, the percentage for development expense becomes much greater.

The writer has observed with growing interest that other appraisals of electric railways all point toward the conclusion that that railway is fortunate indeed that can develop a sufficient business to yield a fair return on the cost of the physical property without incurring a development expense (a going value expense) of at least 30 per cent of the cost of its physical property new. And, if, as seems likely, the average depreciation of all electric railways is about 20 per cent, as determined by appraisal on the straight line theory, then the development expense will average about 50 per cent of the cost new, which is to be added to the depreciated plant value to obtain the total value of the plant and its going business. No man can say exactly what the average percentage will ultimately be found to be, but it is evident that not merely the public but experienced engineers will be surprised by the facts that are now in process of disclosure as a result of numerous electric railway appraisals.

The author of this paper gives a table of rates of depreciation used by different appraisers, and he speaks of them as having, in effect, "largely become law." This is apt to be misleading, for, of course, the use of a rate of depreciation by no appraiser gives it even the semblance of law, nor does the acceptance of an appraiser's estimate by a public service commission add much to the credence that engineers or court should necessarily give to the truth of the figures.

Many of the rates of depreciation given in the author's table are rates based upon engineering guesses as to the life of machinery, and the life is a life determined by obsolescence or inadequacy.

The writer found that the life of locomotives and cars used by several large railway systems had averaged 28 years. It is quite generally known that many locomotives are in use on European railways after a life of more than half a century, showing that depreciation of locomotives in America has been almost entirely a matter of economic inadequacy. Locomotives are quite typical of other machines. With the exception of a few plant items that depreciate by rotting, such as wooden cross-ties and poles, and a few items that depreciate by abrasion, such as rails, trolley wire and pavements, there are scarcely any items given in the author's table that have a depreciation rate that has not been estimated on the basis of life lost through obsolescence or inadequacy. This being so, it becomes illogical to attempt to appraise the depreciation of many items of a public utility by mere inspection. The writer believes he was among the first, if not the first, to take cognizance of this point in making an appraisal of great magnitude. At least the writer was the first engineer of a public utility commission to abandon entirely any attempt at inspecting all the property of public utilities to determine the depreciation. The writer prepared plant mortality tables of all classes of plant units, and from the age of the plant units deduced the depreciation. A description of the method and discussion of the reasons for its use are given on page 1295 et. seq. of the writer's "Handbook of Cost Data."

The author is wrong in his statement that the writer used what the author calls the "fifty per cent method of depreciation." What the writer did do was to call attention to the fact that all depreciable plant, where there are numerous plant units, ultimately depreciates 50 per cent of its wearing value if the plant is properly maintained; and, in the absence of any knowledge whatsoever as to the average age of plant units, it would be reasonable to use the "fifty per cent method" where inspection of plant units indicates that the "fifty per cent method" would yield approximately correct results.

If wooden cross-ties, for example, have been so long in use as to attain a rate of renewal equal to the reciprocal of their total life in years, then it amounts almost to a certainty that their average depreciation is 50 per cent, by the straight line formula. However, even in the case of ties, the writer has seldom been forced to guess, but has found it possible to deduce the average life either from the accounting records or from the engineering records.

As for inspection of such plant units as wooden ties or poles to determine depreciation, the writer can find little good reason, No man can look at the average tie or pole in use and tell its probable remaining life within a wide margin of the truth. A far closer estimate can be made if the average age is known.

Field inspection of wear of rails, trolley wire, etc., is more satisfactory, but even that can often be largely eliminated. Thus, for rails or trolley wire, careful measurements of wear due to a known number of cars will disclose the rate of wear; and from such data can be calculated the probable future life of other rails or trolley wire if the average density of traffic is known. But the life of rails is not always a function of the rate of wear, so that neither inspection nor calculation based on wear measurements will always disclose the true depreciation. Increased weight of rolling stock has been a most potent factor in causing rail renewals in the past, for rails have become inadequate because of the greater wheel loads they have been required to support. Nor is this all. Just as one change in chemical composition of rails led to the replacement of iron by steel, so other changes are now causing replacement of common steel by steel alloyed with ferrotitanium and other metals.

View the whole subject as we may, we are driven inevitably to the conclusion that inspection is apt to be a very misleading method of determining depreciation for almost any kind of plant unit, and that for most kinds of plant units inspection is the most misleading method that can possibly be used. No amount of inspection can show the rate of depreciation due to obsolescence or inadequacy.

A very strong argument can be made in behalf of estimating depreciation solely on the rate of loss of life due to wear, tear and disintegration by natural forces. While this method is seemingly to be desired by public service corporations whose property is being appraised for purposes of rate making, it proves to be a boomerang the moment consideration of the maintenance expense begins, for then a corporation naturally and rightly wants to be permitted to take out of earnings enough to provide for depreciation due to obsolescence and inadequacy.

The writer believes that no man can accurately estimate *future* depreciation due to obsolescence or inadequacy, but the only safe and fair way is to base future estimates of depreciation on past experience. Then the rates of depreciation thus deduced should be applied both in appraising depreciated values and in providing sinking funds or depreciation reserves out of earnings. It may be demonstrated mathematically that a public service corporation, the weighted age of whose depreciable plant is less than $\frac{1}{R}$, is the gainer the higher the rate of depreciation assigned to the plant, R being the rate of fair return. Thus, if the rate of fair return R, is 8 per cent (0.08) we have $1 \div 0.08 = 12\frac{1}{2}$ years as the critical age. If the weighted age of the plant is less than 12½ years, then the more the estimated depreciation rate exceeds what it actually should be, the greater is the corporation the gainer by the error, provided the same rate of depreciation is used in estimating allowable amounts for sinking fund deposits. This formula $N = \frac{1}{R}$ for ascertaining the critical age can readily be proved true by the application of algebra, or by taking a few specific numerical examples.

Nearly all public service corporations, and steam railway companies in particular, have failed in the proper presentation of their cases to commissions and courts. This has been due to their ignorance of the problems of appraisal and rate making. They have fancied that their own operating engineers, officials and attorneys could readily prepare both the data and the arguments. Never was a more serious blunder made. Their engineers have usually not deeply studied either appraisals or rate making, and their lawyers have usually understood neither end of the problem. Finally, railway commissions themselves have often erred, because, while they have regarded appraising as being an engineering problem, they have not always regarded rate making as also involving equally important engineering problems.

Depreciation, as we have seen, affects not merely the problem of appraisal, but it gravely affects the matter of estimating operating expenses. The operating expenses of any single year are usually not typical, that is, they may be either higher or lower than an average over a long term of years, due to variations in the cost of renewals of plant units—*i.e.*, depreciation costs. When a plant is young its current repairs are smaller than they will be later on, and renewals (depreciation costs) are usually absent entirely in a young plant. It is an engineering problem, therefore, to determine what the maintenance expenses are going to be, and therefore it is an engineering problem to estimate proper allowances for maintenance during a typical or average year. No other kind of a year can be justly used as a basis for rate making. This is not the only reason why rate making is largely an engineering problem, but, even if it were, it would be sufficient reason why expert appraising engineers are needed not only in making appraisals of existing property but in appraising maintenance expenses.

Railway corporations have usually failed to secure an adequate allowance for "going value" or development expense. Most of them have secured no allowance at all, entirely because they have made no careful study of appraisal problems. They have often lost their development expense and with it has gone also that part of the development expense due to depreciation. They have known intuitively that they were being deprived of their rights under the guise of law, but they have not been able to give adequate reasoning for their belief in the injustice they were suffering. Driven to extremes they have often lied about the value of their physical assets, when they could have secured all that they were fighting for in the way of total values by merely proving their development expense from their own accounting records.

Recently the Wisconsin Railroad Commission has adopted a modified form of the above described deficit method of calculating development expense, and the commission has ruled that in calculating development expense the old operating costs of a company must be increased by a sufficient sum to cover the actual depreciation. This is one of the most important steps ever made by a public utility commission, and probably marks the beginning of the general adoption of a wholly rational method of ascertaining that hitherto elusive element of cost—development expense or "going value".

Whether past depreciation should be amortized from future earnings or not is largely a matter of sentiment. In fact, whether development expense (going value) should be amortized or not is also a matter of sentiment. It probably will make little difference either to the public or to the public service corporations what procedure is adopted, for whether development expense remains as a source of revenue to a company or whether it is amortized, the company will get its *quid pro quo*.

Henry Floy: The rather close connection and joint discussion of Mr. Byllesby's and the author's paper, sometimes makes it difficult to analyze and reply to certain of the speakers' arguments.

The careful and lengthy discussions of the paper under consideration, by men of such prominence as those who have contributed, indicate the wide-spread interest and importance of the subject; at the same time clearly substantiating the authors opinion that there exists a notable lack of uniformity of nomenclature and a wide diversity of opinion in matters relative to "Depreciation."

The author appreciates the efforts of several of the contributors in their attempts to clarify and properly define terms. This would be more acceptable were it free from a spirit of sarcasm apparent in the discussion of one participant, but so out of place before an engineering society. Aside from any attempted definitions which may be purely academic or put forth as a species of mental gymnastics, most engineers agree with the author that utility has a value which may be expressed in dollars. If not, the values indicated by the curves Nos. 3, 4 and 5, in Fig. 1, may not be expressed in dollars any more than curve 6, and the only value that may be attached to the property being appraised, if the term relates exclusively to barter and sale, is the second-hand or scrap value, which all informed engineers will agree is not the basis on which any appraisal has been or is being made for determining the physical values of an operating concern. Because John Stuart Mill years ago, or other political economists, once attached a certain meaning to the word "value" does not signify anything with regard to the present use of the noun. Words change their meaning daily, and the word "value" may properly be used to measure utility, the original value of which has perhaps been determined through purchase.

As has been suggested by several speakers, the Institute could appropriately take under consideration the proper definition of terms used in connection with the subject of "Depreciation," coöperating with the other national societies in this matter. The National Electric Light Association has already a committee at work on this subject.

Several prominent engineers indicate that in their opinion, for rate making purposes, certainly, the basis for valuation is the cost of the physical property reproduced as new, plus certain development expenses. This is a very satisfactory showing and indicates decided progress. Mr. Arnold explains and accepts this basis frankly, while Mr. Gillette comes to the same conclusion through the inclusion of what he unfortunately terms "development expense." His application of this term to what has generally become to be known as "going value" and has been so used for years by the Wisconsin Commission, will hardly be accepted by informed engineers. Mr. Gillette himself seems to find it necessary to use "going value" to explain what he improperly calls "development expense". It would seem as if those who differ from the author in the use of terms or definitions set out by him, should advance sound argument for substitution of terms they propose rather than mere expression of preference, or what they have been accustomed to do as against the wider use and more general custom, which the author has attempted to follow.

As stated by the author, the tables showing accepted rates of depreciation, which include as a rule some allowance for obsolescence and inadequacy, cannot be applied indiscriminately, and must be used conservatively. They are given as indications of what has been done; in fact much of the entire paper has been written to show the line of procedure heretofore followed. It would seem that we can only advance by a thorough understanding and knowledge of what other people are doing in treatment of the subject of depreciation, and these tables are given because they show figures which have been approved in important cases, and what fairly may be expected by those who are interested in operating companies when they have to appear before commissions or courts. The readjustment of rates based on the use of such figures and their acceptance both by the Public Service Commissions and public utility companies, certainly establishes them much more firmly than mere engineer's opinions, and gives them in effect the semblance of law.

Considerable of the discussion apparently relates to methods of procedure applicable to newly organized or recently started companies, where either the application or omission of theoretical depreciation can be, made without injury to the interests of those who have invested their money. This condition, however, does not apply to old corporations and it is unfair to take advantage of those who have already invested their money, and are unable to take it out, to apply too strictly rules such as those covering theoretical depreciation, where such application will result in the confiscation of property running into perhaps millions of dollars. This is evidenced for example, in the case of some engineers who, while claiming that curves Nos, 3, 4 or 5 Fig. 1, are those to be used in determining the present value of property, are very careful to avoid trying to demonstrate the absolute accuracy of any one of the three curves, although the use of one or the other would result in a difference of several millions of dollars, as has been shown for example, in the valuation of street railway properties in New York City. The use of one curve or the other, admittedly, is largely one of preference or convenience, and being based on an assumed theoretical life always results in discussion in the endeavor to prove the truth of the assumption, which is not absolute.

Several of the speakers apparently failed to grasp the author's distinction between "absolute" and "theoretical" depreciation, and the fact that these are *both* considered in determining present value only, that "theoretical" depreciation alone is used in determining annual rates of exhaustion of life. Mr. Hoxie seems unable to appreciate that a yearly rate of depreciation has nothing whatever to do with the total absolute depreciation, and his illustrations as to rulings of Commissions, assume an ignorant commission unable to revise its rulings, as it finds the amounts laid aside for depreciation are larger than required. Further, he seems unacquainted with the very wide practice of corporations and the rulings of at least one Public Service Commission, practically prohibiting the building of extensions out of excess earnings, which many consider contrary to the best policies now in vogue. Of course the author was endeavoring to cover the usual case that exists and not the exceptional, covered by the illustration. The author has not conceived of "two separate rates of depreciation" applied to the same property, nor does he agree that the appraisal must include a deliberate judgment of the value of useful service remaining as it is present service, not future service, which the public is interested in, and upon which the rate of return must be based. In the Consolidated Gas case, the Supreme Court did not tell us to figure two kinds of depreciation. It did tell us to figure one kind of depreciation, and that is what the author has called "absolute" depreciation, which is to be used in determining the present value, on which rates are based. It did tell us that no "theoretical" depreciation should be deducted in establishing the basis on which to estimate fair return. In the Knoxville Water case, the Court clearly states that the original investment, regardless of "absolute" depreciation, is not the basis for figuring a fair return, and furthermore that proper allowance, as a part of operating expenses, should be made to cover the wasting away of physical property. Mr. Hoxie evidently agrees with the engineer of the Public Service Commission, that it is a very easy matter to appraise the Third Avenue R.R. by the "50 per cent method", which basis the Public Service Commission accepted in part, and obtained a depreciated value which does not compare with the value or appearance of the property to anyone who knows it, and demonstrates as well as anything can that "theoretical" depreciation is purely theoretical.

Mr. Foster states that "repairs are continually made in the endeavor to keep the property up as near its original value as possible". This is evidently an over sight by Mr. Foster, as of course he recognizes that repairs are made not for the purpose of keeping property up towards its original value, but to maintain it in good, operating order. He is also mistaken in stating that "It is utterly impossible that taking at any moment the value of the whole property could be 100 per cent of its original value" as it can be easily recognized that a sudden rise in the value of real estate of a marked difference in the price of labor and material could easily result in showing by appraisal, the value of the property at 110 or more per cent of its original cost. In fact the values of 75 per cent or 85 per cent so frequently used as that of property in good condition depends on how much of the physical property is of long life, or whether the relative amount of total investment is largely in real estate or road-bed, which increases rather than decreases in value with age.

With regard to the Springfield Street Railways, the author entirely agrees with Mr. Foster that the investment in horse properties should have been amortized out of earnings, if the latter was sufficiently large to permit such amortization, otherwise the value of the horse railways must be left in the capitalization, as indicated in the paper under "Total Depreciation" for example, although nothing of the original physical property remains for identification.

Of course ordinary wear and tear maintenance, renewals, replacements, obsolescence, inadequacy, must be taken care of eventually as a part of operating expenses, and paid for by the public; there can be no question on that point if investors are still to be found willing to put their money in public utility properties.

At first thought and superficially, it would seem that the sum of the plant value (the present value determined by appraisal) and the depreciation fund (where one is necessary) should, at a given time, equal the original investment. As a property kept in good operating condition will ordinarily not be found to be in a condition below 75-85 per cent of cost of reproduction, a fund larger than 15-20 per cent would never be required even on the theoretical basis proposed by some engineers, and as a practicable matter, a sum equal to 3-5 per cent of the original value, would ordinarily be amply sufficient for a property uniformly maintained.

The ambiguity, if such exists, which Mr. Miller seems to find with regard to the author's separation of development expense from physical values, doubtless arises from the attempt to include with the physical values, those percentage items which are practically fixed and uniform in all cases, such as engineering expense, allowance for incidentals, omissions, etc., and to put in a separate class under the head of development expense, those items which vary widely with local conditions, and individual management. There certainly was no suggestion that development expenses were any less a necessary part of the total outlay required than were the physical costs, but the engineering expense for example is practically always 5 per cent, while the costs of obtaining a franchise or the legal expenses, must be figured for the actual case under consideration and vary widely. It would hardly seem fair in view of the statement made in the paper under "Total Depreciation", to state that the author criticizes the action of companies in charging to capital account replacement due to obsolescence. This is only so in case the earnings have been sufficient to write off the obsolescence Mr. Miller says " Depreciation, as well as other loses in early years should be capitalized until the property is earning all expenses." Certainly the Public Service Commissions and engineers generally will not agree with this statement unqualified, as it would mean that poorly managed or evidently ill advised investments should be allowed to continue capitalizing losses indefinitely. There must be some limit to the capitalization of these early losses, and while a legitimate and reasonable amount may be capitalized if the earnings are too small to cover the depreciation and obsolescence, such procedure comes close to encroaching on dangerous and unstable ground. It would be interesting for Mr. Miller to cite cases in which depreciation has been determined by estimating the amount " required to put the apparatus in a condition that is practically as good as new " for certainly it is not " the usual process."

The advance copies contained some typographical errors so that the clause quoted by Mr. Miller is not clear; it should have read " while usually preferable, there exists no necessary reason for always writing off certain costs, such as engineering, incidentals, etc." the author's view being apparently in accord with Mr. Miller's, namely that original engineering expense need not necessarily be written off with the depreciation of the physical property which may be renewed without such engineering expense. For example the renewal of rails in track would be done by the operating force without any special engineering expense; therefore the original engineering cost remains in the property, regardless of the physical condition of the rails. Practically the same method of determining going value, (called " development expense " by Mr. Gillette, and shown in his tables 1 and 2) has been recognized and used by the Railroad Commission of Wisconsin for some years. It has strong claims for consideration, and if judiciously used, is applicable in many cases. Mr. Gillette truly states that no amount of inspection can show the rate of depreciation due to obsolescence or inadequacy, but neither can theorizing determine the rate. If Mr. Gillette proposes to determine all depreciation from records and computations made in an office, it would seem as if his results were entirely theoretical and hypothetical. As it is practically impossible for any engineer to determine the amount of " theoretical " depreciation from an inspection of apparatus, does not the whole question of such depreciation, which must be based on examination of records as to dates of purchase, with an assumption as to probable life, result only in speculative values; which while possibly of service in determining the price for bargain and sale, has nothing whatever to do with the value on which capitalization should be based or rates fixed, provided an inspection proves the property is well maintained.

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INDUCTION MACHINES FOR HEAVY SINGLE PHASE MOTOR SERVICE

BY E. F. W. ALEXANDERSON

The experimental results and investigations presented in this paper have the object of showing the possibilities of operating polyphase motors from single-phase circuit, particularly with a view of the use of such a system where heavy starting duty is required. At various times there have been suggested schemes for changing single-phase current into polyphase current for such purposes, but those schemes have never been taken very seriously on account of their ineffectiveness in producing a balanced polyphase current.

The reason why the author feels justified in presenting these data to the Institute is, that he has succeeded by the scheme described in producing a balanced polyphase current by an apparatus which, in cost and weight, is only a fraction of the driving motors, the motors being ordinary polyphase motors with the same starting and running characteristics as such motors used on ordinary polyphase circuits.

EARLY TYPES

A well known scheme, often thought of in connection with changing single phase current to polyphase, is the use of an induction motor, as shown in Fig. 1. Two terminals of the induction motor are connected to the single phase line, whereas, all three terminals are connected to the driving motor. If the first mentioned machine, which may be classified as a " phase converter ", runs at full speed it generates a polyphase voltage which is available for starting the driving motor. However, the output of the phase converter is very unbalanced, and the starting torque of the motor is so much reduced that the system has found application only in exceptional cases.

The theory of the phase converter can be treated with greater facility if both machines are considered as quarter phase instead of three phase machines, and this assumption will, therefore, be used in the following:

Considering the quarter phase connection, as shown in Fig. 1, it is apparent that phase *A* is fed directly from the line, whereas phase *B* of the motor is fed through the medium of the windings of the phase converter. In other words, whereas the working current in phase *A* of the motors needs to flow only through one winding, the working current in phase *B* must flow through three windings, that is, phase *A* of the converter, phase *B* of the converter and phase *A* of the motor. The net result is as shown by theory as well as tests, that the maximum starting torque of such a combination is between 45 per cent and 50 per cent of the torque of the same motor fed from a polyphase circuit. Under those circumstances it would be impractical to use such a scheme for starting and accelerating duty, because the maximum output of the driving motors is usually the limiting feature of the design.

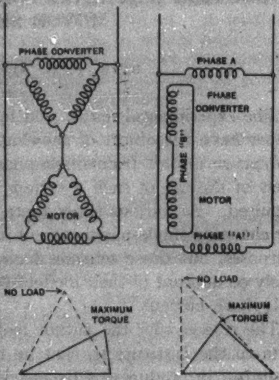

Fig. 1

Nature of the Improvements

The scheme presented by the author is a development from the induction phase converter shown in Fig. 1; however, with the introduction of such improvements that the starting torque of the main motors is the same as on polyphase current instead of less than one-half of that value.

The reason for the ineffectiveness of the phase converter in accordance with Fig. 1 is the voltage drop in phase *B*, and, furthermore, the phase displacement between the voltage of phase *B* and the voltage of phase *A*. The starting torque of a quarter-phase motor is proportional to the product of the voltages on phase *A* and phase *B* multiplied by the sine of the phase displacement between phase *A* and phase *B*. To illustrate this, it can be said that the starting torque is proportional to the triangle representing a complete polyphase voltage impressed upon the motor. The voltage triangles for an induction phase converter delivering current under the conditions of maximum torque of the motor is shown under the corresponding diagrams in Fig. 1.

It is evident, at first sight, that the voltage at the terminals of the motor is very far from a balanced polyphase voltage. In order to improve these conditions it is necessary to correct the phase displacement as well as increase the current in phase *B*. In attempting to accomplish this, the first improvement which suggested itself was to connect the motor in series with the phase converter. In doing so the phase converter is forced to act like a series transformer between phase *A* and phase *B*, transforming the current from one winding to the other and displacing it at the same time by approximately 90 deg. This arrangement in itself effects a considerable improvement because the phase converter, looked upon as a series transformer, maintains a comparatively good ratio between the primary current and the secondary current, and the ratio of currents and phase displacement rather improves by increasing load, whereas, the secondary voltage in the multiple connection decreases rapidly at increasing load. As a net result of this arrangement, according to experiment, it can be stated that the starting torque is about three-quarters of the starting torque with polyphase current. Such a result, although a considerable improvement, would scarcely be acceptable. The reason for the lack of effectiveness is the fact that all the lagging current that must be supplied to phase *B* of the motor must be transformed twice by the phase converter, passing from stator to rotor and back from rotor to stator, thereby causing a considerable drop in voltage.

The method which has been found to overcome this difficulty is to interpolate in phase *B* a voltage, derived from the line, so as to create artificially a phase displacement between the output of the phase converter and the input of the motor. By doing so the phase converter is allowed to give an output of leading current instead of lagging current, whereas, the motor receives lagging current as before. It should be noted that the current flowing in the two machines is the same, but it has the effect of lagging current in one and leading current in the other on account of the artificial phase displacement between the voltages. The result is that the current output of the phase converter is not demagnetizing, but tends to increase the voltage, and, in fact, as will be shown in the following, the voltage and current of the secondary phase can be entirely regulated by selection of a suitable voltage for interpolation between the windings. The diagram of connections is shown in Figs. 2 and 3. In Fig. 2. an autotransformer is used for supplying the interpolated voltage whereas in Fig. 3 the line voltage is used, while phase *B* is eventually wound with a correspondingly greater number of turns.

GENERAL THEORY

Next to the fact that the system is operative the most important question to be answered is, what are the characteristic curves and the efficiency and power factor of the combination.

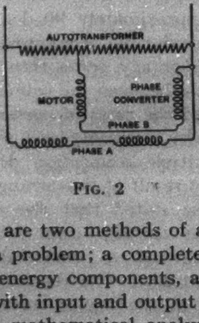

FIG. 2

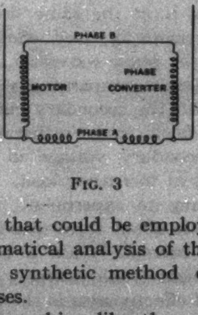

FIG. 3

There are two methods of analysis that could be employed for such a problem; a complete mathematical analysis of the electrical energy components, and the synthetic method dealing only with input and output and losses.

The mathematical analysis of a machine like the ordinary single-phase induction motor and even the transformer have led to considerable literature, and new contributions to the same are being made all the time. It, therefore, appears that even in problems where the methods are as well agreed upon as those mentioned, there is considerable latitude for the personal point of view of the investigator. The problem before us is a good deal more complicated than those mentioned, and for this reason the complete mathematical analysis will not be attempted, but the paper will be confined to the statement of the premises and deriving the most important results by a synthetic method. In dealing with direct current the synthetic method is extraordinarily simple and used exclusively. All that needs to be considered is the energy terms, input, output and losses, which are all measured in watts. With alternating current there are the wattless components to be considered which are measured in volt-amperes. There seems, however, to be a law for dealing with wattless volt-amperes which is almost as definite as the conservation of energy. For practical purposes it can be stated that all the wattless volt-amperes delivered to a circuit can be traced as losses of volt-amperes or outputs of volt-amperes in some parts of the circuit or of its subsidiary circuits connected to the same by induction or rotation. A certain quantity of volt-amperes can be changed to another quantity by change of frequency on account of relative rotation of the winding. The quantities are, however, strictly connected by the relative frequency, so that it may be said that the volt-amperes divided by the frequency is a fundamental quantity or magnetizing effort, which follows a law analogous to the conservation of energy.

A magnetizing effort can be generated only by a battery, commutator or other rectifying device, and is usually introduced in alternating circuits through a magnetic field excited by a direct current furnished from the commutator of the exciter. Wherever commutators occur in an alternating circuit allowances must be made for the magnetizing effort generated by these commutators. However, in the cases of purely inductive circuits like those in the problem before us, the law applies without an apparent exception. Each alternating field consumes a definite amount of volt-amperes for its excitation, and each current flowing in windings consumes a certain amount of volt-amperes due to its leakage reactance. All that is necessary in order to find the power factor of a certain combination of alternating fields, is to sum up the volt-amperes needed to excite the field, and the leakage volt-amperes created by the current in the windings. These volt-amperes added together constitute the total wattless volt-amperes of the machine combination. The energy components are figured in the ordinary way, adding together output, core losses and copper losses as determined by the currents flowing in the various circuits. After finding in this way the total energy input and the total wattless kilovolt-amperes, the total input is found as the square root of the sum of the squares of the energy input and the wattless input. The power factor can then be found as the ratio of energy input to total input.

In order to use this method it is evidently necessary to know the strength of the various fields and the values of the various currents. However, it is not necessary to know the phase relations between the fields and the currents, or the relative phases of currents and voltages. The values of the individual quantities are comparatively easy to ascertain, whereas, a knowledge of the phase relations requires a complete mathematical analysis of the components. Applying the above to the phenomena in the machine combination shown in the diagrams, Figs. 2 and 3, there are only two currents to be dealt with.

Phase winding *A* of the motor is connected in series with phase winding *A* of the phase converter, and it is only necessary to assume a value of current for those two windings. The corresponding value of current in phase *B* could be determined graphically or mathematically in accordance with the vector diagram, Fig. 4, but for the sake of calculating the power factor it is only necessary to know, as an experimental fact, that the voltage interpolated in phase *B* through the winding of the main transformer can be regulated so as to give the same current strength in phase *B* as in phase *A*.

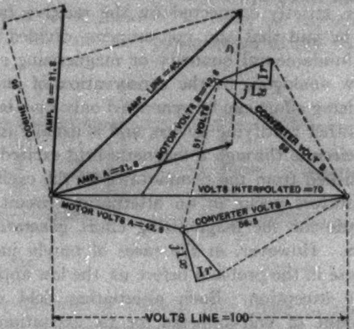
COSINE = .90
AMP. B = 31.8
AMP. LINE = 45.
MOTOR VOLTS B = 42.8
51 VOLTS
n
Ir
jIx
CONVERTER VOLT B
68
AMP. A = 31.8
VOLTS INTERPOLATED = 70
MOTOR VOLTS A = 42.8
CONVERTER VOLTS A
56.5
jIx
Ir
VOLTS LINE = 100

FIG. 4.—Vector diagram for starting condition

If the magnetization and leakage reactance of the phase converter as well as the motor is known, it is possible to figure out immediately the total wattless volt-amperes consumed by the alternating fields.

Fig. 4 shows the complete vector diagram for the starting condition. The resistance in the rotor circuit of the motor has been selected so as to give maximum torque for any given voltage. The values of voltages and currents are given with reference to a line voltage of 100 in order to make the information contained in the diagram more directly useful for application to any other voltage. In such a case, all the volts and currents should be increased in proportion to the voltages, and the kilovolt-amperes and kilowatts and torques in ratio of the squares of the voltages.

The voltage interpolated in phase *B* has been selected 70 per cent of the line voltage because it was found experimentally that this gave an equality of current in phase *A* and phase *B*. The phase relations as given on the diagrams are obtained from the average of several measurements made at different voltages, but reduced to 100 volts, as stated above. The diagram shows vectorally the current in phase *A* and phase *B*, and also how those currents are combined into the total line current, using 70 per cent of the current in phase *B* for one of the vectors. This is due to the ratio of transformation in the transformer supplying the interpolated voltage. The line current obtained in this way agrees in value as well as in phase with the line current found by ammeter and wattmeter measurements. In the diagram is also shown the phase displacement or deviation from exact quarter-phase relation. The cosine of the angle of deviation is 0.95. Hence, it can be concluded that the starting torque is reduced by 5 per cent from what it would have been with exact quarter-phase current.

CHECKING OF TEST RESULTS BY CALCULATION

Of all the factors that enter into the complete analysis, as indicated by the vector diagram, it is only necessary for practical purposes to be able to determine the following:

Amperes line.
Power factor line.
Torque.

It will, therefore, be shown how these quantities can be figured out from the fundamental data of the machine.

The machines used in this test were two 25 h.p., six-pole, 60-cycle, quarter-phase motors, with a normal voltage of 220. One of the motors used for the phase converter was provided with a squirrel cage rotor, and the other with a phase wound rotor and collector rings.

The following are the constants of the machine:

Motor exciting admittance	$0.014 + j0.095$	per phase
Motor impedance	$0.39 \;-j0.57$	" "
Phase converter exciting admit	$0.01 \;+j0.095$	" "
Impedance	$0.26 \;-j0.57$	" "

In order to make these constants available in a convenient form for calculation of the wattless kilovolt-amperes and losses at various voltages and loads, the fundamental curves shown on Fig. 5 have been plotted giving the wattless kilovolt-amperes and losses per phase of the two machines. For the sake of convenience, these curves refer to voltage per phase of 100 and the corresponding values of current and kilovolt-amperes for any other voltage are found respectively by proportionality and square of the voltage ratio, as stated above. The fundamental curves for kilovolt-amperes per phase are figured as follows:

i_1 Amperes secondary	$i_1 E$ kv-a.	$i_1^2 x$ kv-a.	$\sqrt{(i_1 E)^2 - (i_1 x)^2}$ kw.	Wattless kv-a.	Input kw.	Input kv-a.	Ampers primary.
0	0	0	0	0.95	0.1	0.96	9.6
10	1.0	0.057	1.00	1.01	1.1	1.45	14.5
20	2.0	0.228	1.99	1.18	2.09	2.35	23.5
40	4.0	0.912	3.89	1.86	3.99	4.42	44.2
60	6.0	2.05	5.64	3.00	5.74	6.47	64.7

The fundamental curves for the converter are also shown in Fig. 5 and are calculated in the same way.

Applying this data to the starting test it is found that the wattless kilovolt-ampere per phase of the motor at 46.2 volts and 31.8 amperes is 0.7 kv-a., the wattless kilovolt-ampere in phase *A* of the converter at 56.5 volts is 0.79 kv-a., and in phase *B* at 58 volts is 0.81 kv-a., making a total wattless kilovolt-ampere of 3.0. The input of the motor per phase is 1.31 kw., and the total losses in the converter are 0.26 kw., giving a total input line of 3.14 kw. If the kilowatts found in this way are combined with the wattless kilovolt-ampere the power factor is found to be 73 per cent. For comparison it can be stated that the measured power factor is 72.5 per cent.

So far it has been assumed in the above calculations that the motor is supplied with a true quarter-phase current. It remains to determine the phase displacement between the currents in the two phases in order to find the decrease of starting torque due to deviation from 90 deg. displacement. Actually this deviation depends only upon the magnetizing current in the converter. The motor, like any induction motor, is magnetized by the phase displacement between the current in the rotor and the current in the stator, whereas, the phase converter is magnetized by the relative displacement of stator current in phase *A* and phase *B*, or, to be more exact, by the deviation from quarter-phase relation. This is due to the fact that the load current that is absorbed by one phase is discharged by the other, so that the magnetizing current is leading with reference to the load current in one phase, and lagging with reference to the other. Thus the total displacement of the two currents is the sum of the two magnetizing currents. In the case represented by the diagram for starting, the sum of the magnetizing current of the converter is 10.2 amperes. Hence, the deviation from quarter-phase relation is the sine ratio of $\frac{10.2}{31.8}$ or 18.5 deg. The cosine of this is 0.95, or the same as has been found experimentally and as indicated on the diagram. The correctness of this theory has also

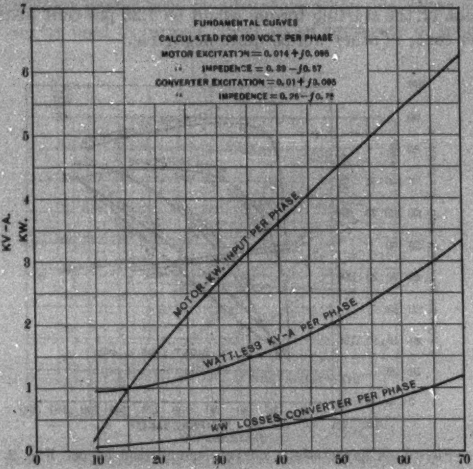

FIG. 5

been checked by direct measurements of torque with true quarter-phase current and with current furnished by the phase converter.

It should be observed that, although the decrease of starting torque of 5 per cent is for practical purposes inappreciable, the difference would be much smaller with a phase converter of such proportions as would actually be used, that is, of a high speed having a comparatively small magnetizing current. Assuming, for instance, that the magnetizing current relative to the output were one-half of what it was in the experimental tests, the correction of the starting torque would be 1.25 per cent instead of 5 per cent; in other words, quite negligible.

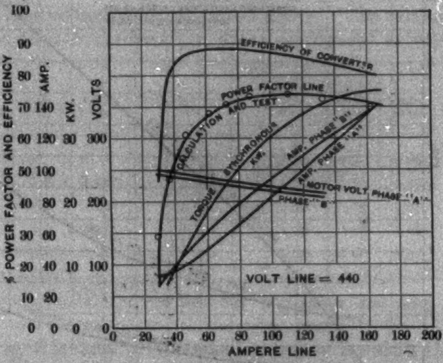

Fig. 6.—Characteristic curves—connection as per Fig. 2

Fig. 6 and Fig. 7 show the characteristic curve for the full speed running condition with interpolated voltages of 60 per cent and 100 per cent respectively. The curve for the power factor is calculated by the method described and the points found by measurement, indicated beside the curve, show the agreement of theory and measurements. The decrease of torque due to phase displacement depends entirely upon the magnetizing current of the converter, and is figured in the same way as for starting. It should only be observed that the correction must be made in watts input as well as output, whereas for starting, the correction applies only to output, the balance being wasted in the secondary starting resistance.

Weight and Size Estimate for Practical Purposes

The tests previously referred to, which were made on two small 60-cycle motors, were undertaken to demonstrate the principle and confirm the theory and methods for calculations, whereas, the quantitative data derived from such tests would have no bearing on the conditions that would exist if the same were undertaken on a larger scale. The value of the system for practical purposes can be demonstrated only by showing the proportions of apparatus such as would actually be used. The system appears particularly to advantage when one phase converter can be used to furnish power to an aggregate of several motors. For this purpose designs have been made of a phase converter of a capacity corresponding to 1,600 motor h.p.

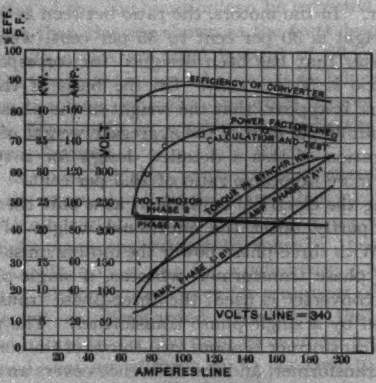

Fig. 7.—Characteristic curves—connections as per Fig. 3

In the first place, the relative proportions will be worth some consideration on general principles. Inasmuch as the energy of one of the phases of the driving motor is supplied by the line, the output of the converter must be substantially one-half of the polyphase capacity of the motor. In the tests described above this was the case, for the machines were of the same size, differing only, as stated, in winding of the armature. If it were proposed for operating conditions to use a phase converter with costs and weight the same as the main motors, the system would scarcely be acceptable. However, with the type of machines which would actually be used, it appears that the weight of the phase converter is only from one-third to one-quarter of the aggregate weight of the driving motors. The converter being a machine running light on its shaft without carrying any mechanical load, can be designed for the most economical speed, and it appears that this would be a peripheral speed which is twice as high as the peripheral speed of the motor. Furthermore, the weight per kilowatt is reduced because a single machine is used to serve an aggregate of several motors. For these reasons it is fair to assume that the active material in the phase converter is used at least twice as efficiently as the active material in the motors. The ratio between active material and total weight also favors the converter. In the motors, the ratio between active material and total weight is 30 per cent to 35 per cent, whereas in the phase converter that has been designed for corresponding purposes the ratio is 56 per cent. On the basis of these general considerations, it appears that the weight of the phase converter would be about 30 per cent of the aggregate weight of the motor. As an illustration of this a detailed design for a typical case shows a still more favorable ratio of 26.5 per cent.

Considering the electrical equipment as a unit there are some gains which partly offset the additional weight of the phase converter. With three-phase power the motors must be supplied from a three phase transformer, whereas, if single-phase power and a phase converter is used, the three-phase transformer can be substituted by a single-phase transformer. The weight of a single-phase transformer is about two-thirds of the corresponding three-phase transformer, and the difference covers an appreciable part of the weight of the converter. Altogether it can be estimated that the total increase in weight of the electrical equipment for single-phase power will be 15 per cent over the corresponding polyphase equipment with the same output and starting torque.

A comparison of the phase converter with a motor-generator set of corresponding capacity gives another illustration of the merits of the system. The single-phase capacity of the converter corresponds to the input of one phase of the motor, or one-half of the total output, whereas, the single-phase motor for a motor-generator set must have the full capacity of the equipment. Thus, the total aggregate capacity of the motors and generators for the motor-generator sets is four times as many kilowatts as the phase converter for the same power in the driving motors. On general principles it should, therefore, be expected that the weight of the motor-generator set would be four times as great as the weight of the phase converter. The figures available for the case under consideration indicate that the ratio would be even a little higher, or about 4.5 times, because the phase converter is favored by the very simple squirrel cage construction.

The converter being of the high-speed type designed for maximum efficiency of the material, it will also have a high electrical efficiency. The estimated efficiency in the instance given is between 96 per cent and 97 per cent. The wattless current absorbed by the converter is also correspondingly small, and the power factor of the combination can be expected to be considerably higher than the one shown in the tests described, particularly when 25 cycles are used instead of 60 cycles. The efficiency of the converter indicated above is an inherent characteristic of the machine, whereas the exact figures for power factor can be given only in combination with the particular motors that may be used.

In all that has been said and written about systems for power distribution, the expression " single-phase " has invariably been associated with commutator motors. It might, therefore, throw some more light upon the subject to consider that the possibilities of the induction motor for single-phase power are far from exhausted, although they have for a number of years been almost neglected or disregarded. Realizing that polyphase induction motors are by far the most economical form of power equipment, and that an addition of 15 per cent to the weight of the electrical equipment will adapt the same for single-phase power with the same output and starting torque, the subject might be reopened for serious consideration.

A paper presented at the 28th Annual Convention of the American Institute of Electrical Engineers, Chicago, Ill., June 28, 1911.

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ELECTRICAL OPERATION OF THE WEST JERSEY & SEASHORE RAILROAD

BY B. F. WOOD

The proceedings of our engineering societies abound in papers and discussions on the merits of steam and electric operation of railroads in which data are used, which to a large extent are lacking in figures taken from the actual cost of operation. A general impression prevails that operating officers of railroads will not consent to the publication of their operating costs. This to some extent may be true, but where such figures are correctly understood and properly used there should be no objection to their publication.

When the question of presenting certain data pertaining to the operation of the electrified portion of the West Jersey & Seashore Railroad before the American Institute of Electrical Engineers was discussed with the management of the Pennsylvania Railroad, the reply was made that not only would the information be furnished but that it would be a pleasure to have such information made public through the proceedings of the Institute. The following data were taken direct from the operating records with only such additions as would make them more readily understood. No effort has been made to curtail or to modify in any respect the data selected.

It is the object of this paper to present these data in as concrete form as possible without comparison with the operation of the parallel steam service, and no attempt will be made to analyze or compare the data with any that have heretofore been presented.

This paper will be of value if railroad engineers are encouraged to present before the Institute similar data, and if some standard form for the compilation of such data is agreed upon. Comparisons could then be made more readily and their value enhanced.

It is hoped that a discussion will be developed which will enable operating officers and engineers to improve the efficiency, add to the reliability and reduce the costs of operation of electrically operated railroads.

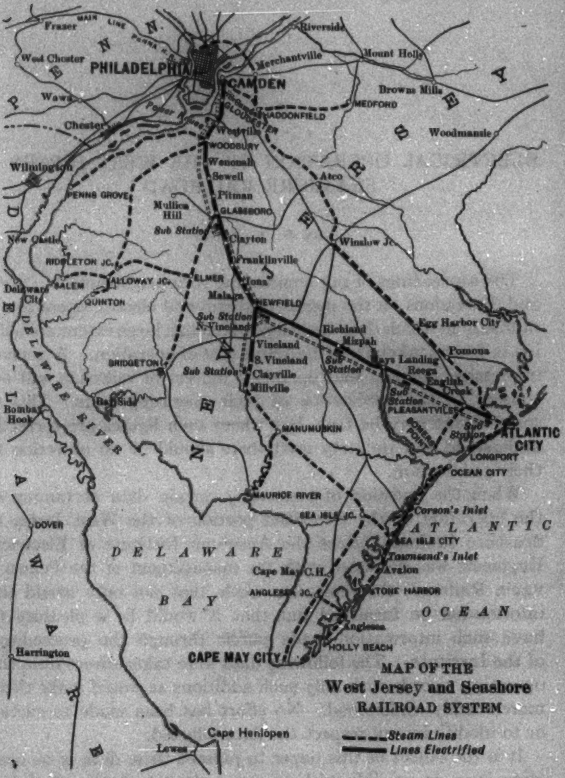
PENN.
PENNA R. R.
MAIN LINE
Frazer
West Chester
PHILADELPHIA
Wawa
Chester
Wilmington
CAMDEN
Merchantville
Riverside
Mount Holly
Browns Mills
MEDFORD
HADDONFIELD
GLOUCESTER
Westville
WOODBURY
Wenonah
Sewell
Pitman
GLASSBORO
Mullica Hill
Sub Station
Clayton
Franklinville
Iona
Malaga
NEWFIELD
Sub Station
N. Vineland
Vineland
S. Vineland
Clayville
Millville
Sub Station
PENNS GROVE
New Castle
RIDDLETON JC.
SALEM
ALLOWAY JC.
ELMER
QUINTON
Delaware City
BRIDGETON
Bay Side
Bombay Hook
DELAWARE RIVER
Woodmansie
Atco
Winslow Jc.
Egg Harbor City
Pomona
Richland
Mizpah
Sub Station
Mays Landing
Reega
English Creek
Sub Station
PLEASANTVILLE
SOMERS POINT
Sub Station
ATLANTIC CITY
LONGPORT
OCEAN CITY
MANUMUSKIN
MAURICE RIVER
SEA ISLE JC.
Corson's Inlet
SEA ISLE CITY
Townsend's Inlet
Avalon
STONE HARBOR
Cape May C.H.
ANGLESEA JC.
Anglesea
HOLLY BEACH
CAPE MAY CITY
NEW JERSEY
DELAWARE
DOVER
Harrington
DELAWARE BAY
ATLANTIC OCEAN
Cape Henlopen
Lewes
MAP OF THE
West Jersey and Seashore
RAILROAD SYSTEM
Steam Lines
Lines Electrified

FIG. 1

No attempt will be made to describe in detail the construction used in the electrification of the West Jersey & Seashore Railroad as complete descriptions can be found by reference to the files of the Electric Railway Journal.[1]

The portion of the line which is electrically operated extends from Camden, via Newfield, to Atlantic City, a distance of 64.6 miles; and from Newfield to Millville, a distance of 10 miles. With the exception of the Millville Branch, which is a single track railroad, the line is double tracked with a third track extending for a distance of about six miles north from Woodbury.

This portion of the W. J. & S. R.R. was originally operated by steam and was a single track line south of Newfield. In the latter part of the year 1905 it was decided to electrify. The work was undertaken in December 1905 and had progressed to such a point that in the early part of July 1906 the first train was moved electrically. Regular operation by electric service was established in September of the same year.

The direct current over-running third-rail system operating at 675 volts was chosen for this installation.

A map of the West Jersey & Seashore Railroad is shown in Fig. 1, from which the electrified portion can be readily followed. The locations of the power station and the substations are shown, as well as the position of the transmission line with respect to the line of the railroad.

In order that the statements of cost of operation and detentions to train service may be more readily understood, the general characteristics of the electrified portion are given.

General Description

Track:

Main line, Camden to Newfield, double track, 100-lb. rails	30.2 miles
Main line, Newfield to Atlantic City, double track, 85-lb. rails	34.4 miles
Main line, South Camden to Woodbury, third track, 100-lb. rails	6.0 miles
Branch line, Newfield to Millville, single track, 100-lb. rails	10.0 miles
Total length of single track, including sidings	150.0 miles

Power Station:

Location: Westville, N. J., on Big Timber Creek, 5.6 miles from Camden Terminal. Rated capacity 8000 kw.

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[1] *Street Railway Journal*, November 10, 1906.
Street Railway Journal, October 12, 1907.

Equipment turbine room:

Four 2000 kw. 6600 volt, three-phase, 25 cycle, Curtis turbo-generators.

Twelve 700 kw. 6600/33000 volt, single-phase, 25 cycle, air blast transformers.

Three 75 kw., 125 volt, Curtis turbo-exciters.

Three 12 h.p. blowers, 20,000 cu. ft. per min. each.

Equipment auxiliary room:

Four Williamson Bros. barometric condensers.

Four I. P. Morris & Co., dry vacuum pumps.

Four I. P. Morris & Co., centrifugal circulating pumps. (three driven by Reeves engines; one by Curtis turbine).

Two Cochrane feed water heaters, each 539 cu. ft. capacity to overflow.

Fig. 2.—Power house at Westville, N. J.

Three Worthington boiler feed pumps.

Two Worthington make-up pumps.

Two Worthington step bearing pumps.

One R. D. Wood accumulator for step bearing, 800 lb. per sq. in., 100 gal. capacity.

One R. D. Wood accumulator for step bearing, 100 lb. per sq. in.

One Worthington oil pump.

One Blake oil pump.

Equipment boiler room:

Sixteen Sterling water tube boilers, 358 h.p. each, with superheaters

Fourteen boilers equipped with Roney stokers.

Two boilers equipped with Taylor stokers.

Hunt gravity return system of coal handling used.

A general view of the exterior of the plant is shown in Fig. 2. In Fig. 3 a plan of the station is shown.

Transmission Line:

Length, 69.3 miles.

Line in duplicate, 33,000 volt, Y connected, neutral grounded.

Poles of chestnut, 45 ft. high, spaced 125 ft. apart—100 ft. at road crossings.

Head guys used every quarter mile, approximately.

Lightning protective ground wire strung on top of poles, 4 ft. above nearest wire, wire of 7 stranded steel galvanized cable, 5/8 in. diameter. Grounded every fifth pole.

Two cross arms on each pole. Top arm 12 ft. long carries 4 insulators; lower arm 8 ft. 6 in. long carries 2 insulators. Insulators 42 in. apart, forming equilateral triangle.

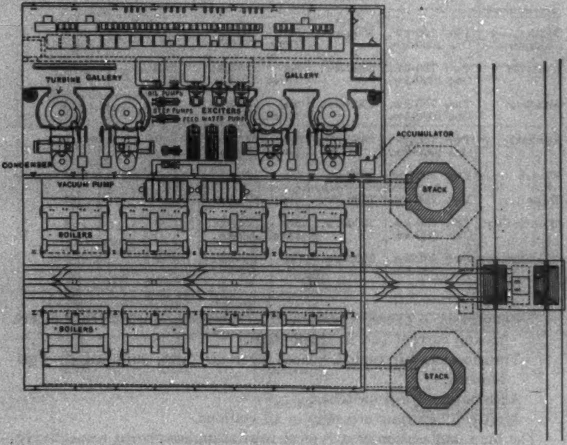

TURBINE GALLERY
GALLERY
OIL PUMPS
STEP PUMPS
EXCITERS
FEED WATER PUMPS
ACCUMULATOR
CONDENSER
VACUUM PUMP
BOILERS
STACK
BOILERS
STACK

FIG. 3.—Plan of power house at Westville, N. J.

Wire, No. 1 B. & S., hard drawn, solid copper.

Wires transposed by one complete spiral between each substation, making a total of seven transpositions.

Signal line and lighting circuit, 1100 volt, single-phase, runs below 33,000 volt line from Camden to Newfield and from Pleasantville to Atlantic City.

Substations:

The high-tension, three-phase current is reduced in pressure and converted to direct-current at 675 volts in eight substations located as follows:

South Camden, 2.3 miles from Camden terminal.
Westville (in power house) 3.6 miles south from South Camden.
Glassboro, 12.1 miles south from Westville.
Newfield, 12.2 miles south from Glassboro.
Mizpah 10.9 miles south from Newfield.
Reega, 10.1 miles south from Mizpah.
Atlantic City, 12.5 miles south from Reega.
Clayville, 8.0 miles from Newfield (on Millville branch).

Equipment:

	Converters	Total cap.	Transformers	Alternating current line panels	Direct current feeder panels
South Camden	Two 750-kw. One 1000-kw.	2500-kw.	Six 275-kw. Three 370-kw.	2	2
Westville	Two 750-kw. One 1000-kw.	2500-kw.	Six 275-kw. Three 370-kw.	2	6
Glassboro...	Two 750-kw. One 1000-kw.	2500-kw.	Six 275-kw. Three 370-kw.	4	4
Newfield....	Two 750-kw. One 1000-kw.	2500-kw.	Six 275-kw. Three 370-kw.	6	5
Mizpah.....	Two 500-kw.	1000-kw.	Six 185-kw.	4	4
Reega.......	Two 750-kw.	1500-kw.	Six 275-kw.	4	4
Atlantic City	Two 750-kw. One 1000-kw.	2500-kw.	Six 275-kw. Three 370-kw.	2	4
Clayville....	Two 500-kw. One 1000-kw.	2000-kw.	Six 185-kw. Three 370-kw.	2	2

Converters, 6-phase, diametrically connected, started from alternating current end in three steps.

Transformers air cooled, placed over air duct, supplied by two blowers.

Automatic oil line switches.

Multigap lightning arresters in all stations.

The plan and section of a typical substation are shown respectively in Fig. 4 and 5. Fig. 6 shows the exterior of the substation at Newfield.

Third Rail:

Length, single rail, main line and branch...........	137.12 miles
Sidings....................................	4.61 miles
Total..................................	141.73 miles

Rails:

Standard P. R.R. cross section and composition, 100-lb. per yd.

Conductivity equal to that of copper rod of 1,200,000 cm. cross section. Located 2 ft. 2 in. from gauge line of track and 3½ in. higher than running rails.

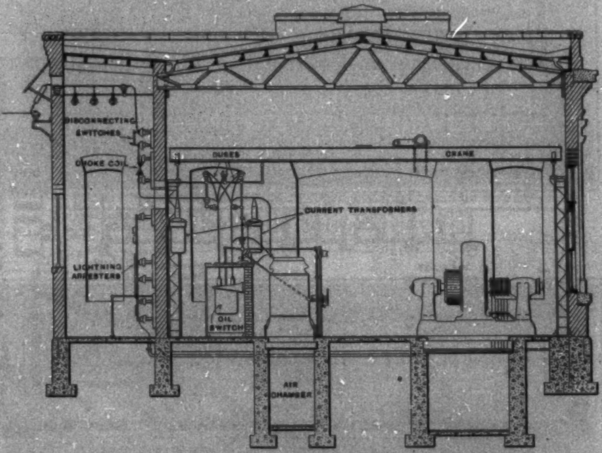
Contact made on top of rail.

Bonded with concealed ribbon bonds, solid copper terminals, pressed into one inch holes drilled in the rail. Two bonds per joint, 500,000 cm. each.

Road crossing jumpers consist of one cable per rail, of 1,000,000 cm., in bituminized fibre conduit laid in concrete.

Jumpers brought out of concrete posts with removable hoods and bonded to rail by two stub-end bonds.

Third rails are provided with protection boards at all stations and for 20 ft. on each side of all road crossings. At stations side protection boards are also used. Top board, two in. plank, supported on castings held by maple posts placed six ft. apart.



TRANSVERSE SECTION OF TYPICAL SUBSTATION

FIG. 4.—Transverse section of typical substation.

The third rails are sectionalized at each substation, each north-bound and each south-bound rail having a separate feeder.

The two rails are cross-bonded at three points between substations.

No feeders are used in connection with third rail.

In Fig. 7 is shown a view of the third rail approach block, the top and side protection for the third rail.

In Fig. 8 is shown the third rail arrangement at cross-over and shows unprotected as well as protected rail.

In Fig. 9 is shown a general view of the yard at Camden, in which all of the third rail is protected.

Trolley:

Length of single wire,

Main line	8.60 miles
Sidings	0.04 miles
Overlapping	0.91 miles
Total	9.55 miles

Wire is No. 4/0 grooved section, supported by ⅜-in. galvanized steel stranded span wires at a height of 22 ft. above track rails.

There are two 750,000 cm. feeders, South Camden substation to Haddon Avenue, Camden, and one 500,000 cm. cable South Camden substation to South Gloucester.

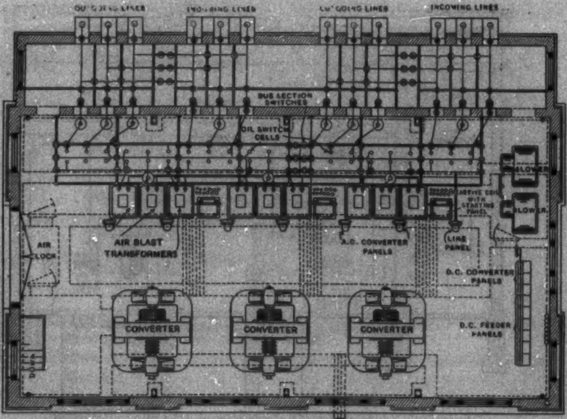

OUTGOING LINES
INCOMING LINES
OUTGOING LINES
INCOMING LINES
BUS SECTION SWITCHES
OIL SWITCH CELLS
REACTIVE COIL WITH STARTING PANEL
BLOWER
BLOWER
AIR LOCK
AIR BLAST TRANSFORMERS
A.C. CONVERTER PANELS
LINE PANEL
D.C. CONVERTER PANELS
CONVERTER
CONVERTER
CONVERTER
D.C. FEEDER PANELS
DOWN
GROUND CONNECTIONS

FIG. 5.—Plan of typical substation.

Track Bonding:

Concealed ribbon bonds used with solid copper terminals compressed into one inch holes drilled in the rail.

Two bonds per joint, 400,000 cm. each.

Special splice bars used to admit bonds.

Bonds tested every six months by means of millivoltmeters and Whitney Bond Tester.

Cars and Equipment:

Car equipment consists of:

79 coaches, seating capacity 58.
2 combined passenger and baggage, seating capacity 36.
6 baggage and mail.
6 baggage.

Total 93 cars.

Coaches weigh 94,500 lb. or 1,630 lb. per passenger.

Electrical equipment of each car consists of two 200 h.p. motors with multiple unit system of automatic control.

Gear ratio, 46:29.

Additional equipment has been authorized consisting of 15 steel coaches, having a seating capacity of 72. The cars will weigh 103,500 lb. or 1445 lb. per passenger.

FIG. 6.—Exterior of Newfield substation

FIG. 7.—Third rail approach block, top protection and side protection

Inspection Sheds:

All inspections and repairs made in Camden shed. Other sheds used for emergency inspection and light repairs.

Camden shed, three tracks, accommodates 9 cars.
Atlantic City shed, two tracks, accommodates 6 cars.
Millville shed, one track, accommodates 3 cars.
Third rail is not continued into sheds, overhead trolly being used.

FIG. 8.—Third rail at cross-over

FIG. 9.—View of electrified yard at Camden terminal

COST OF CONSTRUCTION

A table is included showing the cost of construction in connection with the electrification and includes costs made necessary by electrification. It will be noted that the electrification costs represent less than half of the total cost involved in the change of motive power.

Costs are also presented showing the unit costs of power station transmission line, substations etc.

COST OF CONSTRUCTION

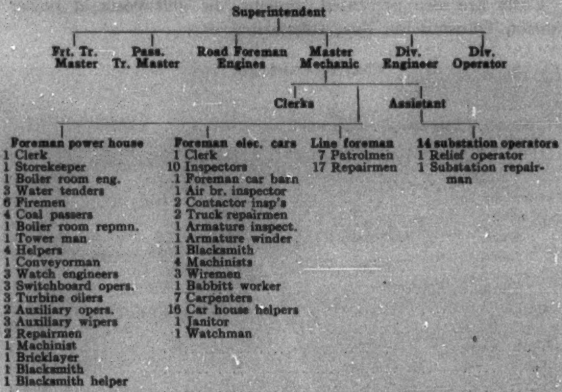
Power Stations:		
Building, stacks, coal and ash handling machinery	$354,000	
Equipment	640,900	
Total		$994,900
Transmission line		241,500
Substations:		
Buildings	72,000	
Equipment	419,560	
Total		491,560
Third rail		557,636
Overhead trolley		80,500
Track bonding		102,659
Cars		1,135,900
Car repair and inspection sheds		46,674
Right-of-way, additional		592,100
Reconstructing tracks		763,800
Constructing new tracks		2,071,000
Terminal facilities and changes at stations		252,400
Signals and interlocking plants		561,900
Changing telegraph and adding telephone facilities		105,100
Fencing right-of-way, cattle guards, etc.		88,400
Miscellaneous items		44,200
Total		8,130,229

UNIT COST OF ELECTRIFICATION

Power station, cost per kw	$124.36
Transmission line, cost per mile	3,485.00
Substations, building and equipment cost per kw	28.90
Third rail, cost per mile	4,235.00
Overhead trolley, cost per mile	4,120.00
Track bonding, cost per mile	684.50
Cars, including electrical equipment each	12,214.00

ORGANIZATION

With the introduction of the electric service the organization of the road was not changed but was expanded to provide for the new duties. A chart of the Motive Power Organization is shown below, which shows the number of employees engaged in the various departments:


Superintendent
Frt. Tr. Master
Pass. Tr. Master
Road Foreman Engines
Master Mechanic
Div. Engineer
Div. Operator
Clerks
Assistant
Foreman power house
1 Clerk
1 Storekeeper
1 Boiler room eng.
3 Water tenders
6 Firemen
4 Coal passers
1 Boiler room repmn.
1 Tower man
4 Helpers
1 Conveyorman
3 Watch engineers
3 Switchboard opers.
3 Turbine oilers
2 Auxiliary opers.
3 Auxiliary wipers
2 Repairmen
1 Machinist
1 Bricklayer
1 Blacksmith
1 Blacksmith helper
Foreman elec. cars
1 Clerk
10 Inspectors
1 Foreman car barn
1 Air br. inspector
2 Contactor insp's
2 Truck repairmen
1 Armature inspect.
1 Armature winder
1 Blacksmith
4 Machinists
3 Wiremen
1 Babbitt worker
7 Carpenters
16 Car house helpers
1 Janitor
1 Watchman
Line foreman
7 Patrolmen
17 Repairmen
14 substation operators
1 Relief operator
1 Substation repairman

COST OF OPERATION AND MAINTENANCE

The cost of operation and maintenance is shown under several headings as follows:

1. Cost of operation in cents per car mile.
2. Cost of operation and maintenance of Westville power station.
3. Cost of maintenance of high-tension transmission line.
4. Cost of operation and maintenance of substations.
5. Cost of maintenance of third rail.
6. Cost of maintenance of trolley.
7. Cost of maintenance of bonding.

Table I shows the cost of operation for the years 1909 and 1910, in cents per car mile, and subdivides the cost of operation into the general headings, repairs, electric equipment of cars; repairs, passenger cars; other maintenance of equipment costs; electric power at car shoes; yard service, shifting cost; motormen; trainmen; train supplies and expenses; total of above; other expenses; total expenses. The table also shows the total car miles per month and the average cars per train. The headings of this statement are probably sufficiently explanatory, other than "other expenses," which includes cost of maintenance of way and structures, despatching trains, telephone and tele-

		Items	January		February		March	
			Total	Cents per kw-hr.	Total	Cents per kw-hr.	Total	Cents per kw-hr.
OPERATION	Labor	Boiler room	1,069.73	0.050	1,073.82	0.058	1,153.75	0.053
		Turbine	803.59	0.038	806.95	0.043	771.83	0.036
		Electrical	133.69	0.006	135.18	0.007	131.53	0.006
		Supervision janitors and watchmen	431.09	0.020	388.56	0.021	371.13	0.017
		Total operating labor	2,438.10	0.114	2,404.51	0.129	2,428.24	0.112
	Material	Coal	7,725.33	0.363	7,049.28	0.378	7,769.57	0.358
		Water	41.67	0.002	41.67	0.002	41.68	0.002
		Lubricants						
		Misc. material	204.62	0.010	121.51	0.007	234.71	0.011
		Misc. charges	123.10	0.005	120.88	0.006	112.40	0.005
		Total operating material	8,094.72	0.380	7,333.34	0.393	8,158.36	0.376
Total operation			10,532.82	0.494	9,737.85	0.522	10,586.60	0.488
MAINTENANCE	Labor	Building	13.04	0.001	4.91	0.000	4.41	0.000
		Boiler room	79.67	0.004	148.68	0.008	191.89	0.009
		Turbine	32.13	0.001	48.48	0.003	118.85	0.005
		Auxiliary apparatus	39.74	0.002	43.22	0.003	33.71	0.002
		Electrical	0.56	0.000	4.95	0.000	13.57	0.001
		Piping	35.74	0.001	39.47	0.002	48.03	0.002
		Miscellaneous	36.49	0.002				
		Total maintenance labor	237.37	0.011	289.71	0.016	410.46	0.019
	Material	Building	8.26	0.000	3.63	0.000	10.76	0.001
		Boiler room	145.62	0.007	304.04	0.016	249.03	0.012
		Turbine	3.19	0.000	125.41	0.007	363.53	0.017
		Auxiliary apparatus	26.35	0.001	144.10	0.008	43.30	0.002
		Electrical	0.60	0.000	0.74	0.000	4.82	0.000
		Piping	9.96	0.001	21.97	0.001	31.81	0.001
		Miscellaneous			52.97	0.003	49.21	0.002
		Total maintenance material	193.98	0.009	652.86	0.035	752.46	0.035
Total maintenance			431.35	0.020	942.57	0.051	1,162.92	0.054
SUMMARY		Total labor	2,675.47	0.125	2,694.22	0.145	2,838.70	0.131
		Total material	8,288.70	0.389	7,986.20	0.428	8,910.82	0.411
		Total labor and material station proper	10,964.17	0.514	10,680.42	0.573	11,749.52	0.542
		Other items charged to station accounts	143.83	0.007	144.86	0.007	137.83	0.006
		Total	11,108.00	0.521	10,825.28	0.580	11,887.35	0.548
		Net output	2,131,000		1,865,300		2,108,600	
		Lbs. coal per kw-hr.	3.311		3.46		3.27	
		Cost of coal per 2000 lbs.	$2.19		$2.19		$2.19	

TABLE II
WEST JERSEY AND SEASHORE RAILROAD
ELECTRIC TRAIN SERVICE
ION AND MAINTENANCE OF WESTVILLE POWER STATION
YEAR 1910

May		June		July		August		September		October	
Total	Cents per kw-hr.	Total	Cents per kw-hr.	Total	Cents per kw-hr.	Total	Cents per kw-hr.	Total	Cents per kw-hr.	Total	Cents per kw-hr.
1,189.43	0.056	1,187.22	0.055	1,314.55	0.047	1,386.02	0.045	1,319.78	0.051	1,239.95	0.056
854.00	0.040	795.88	0.037	857.18	0.031	855.69	0.028	866.82	0.033	866.06	0.039
142.71	0.007	138.75	0.006	141.89	0.005	138.10	0.004	135.46	0.005	139.48	0.006
169.83	0.008	164.15	0.007	181.20	0.007	171.67	0.006	176.60	0.007	179.14	0.008
2,355.97	0.111	2,286.00	0.105	2,494.82	0.090	2,551.48	0.083	2,498.66	0.096	2,424.63	0.109
7,575.21	0.358	8,262.96	0.381	9,849.62	0.354	10,578.06	0.343	9,592.80	0.370	7,908.66	0.355
41.66	0.002	41.65	0.002	41.67	0.001	41.68	0.001	41.68	0.002	41.66	0.002
40.72	0.002	38.27	0.002	47.37	0.002	101.21	0.003	25.74	0.001	35.63	0.001
75.38	0.004	78.33	0.004	147.62	0.005	131.95	0.004	167.39	0.007	169.71	0.008
144.48	0.007	172.80	0.008	124.60	0.004	213.98	0.007	230.77	0.009	127.00	0.006
7,877.45	0.373	8,594.01	0.397	10,210.88	0.366	11,066.88	0.358	10,058.38	0.389	8,282.66	0.372
10,233.42	0.484	10,880.01	0.502	12,705.70	0.456	13,618.36	0.441	12,557.04	0.485	10,707.29	0.481
45.20	0.002	31.89	0.001	8.08	0.000	14.02	0.000	58.29	0.002	20.54	0.001
159.36	0.008	82.21	0.004	104.35	0.004	127.66	0.004	129.76	0.005	97.50	0.004
29.64	0.001	97.10	0.004	52.75	0.002	10.96	0.000	22.57	0.001	51.40	0.002
83.22	0.002	189.25	0.009	84.34	0.003	174.36	0.006	49.20	0.002	22.06	0.001
		15.46	0.001	75.56	0.003	26.21	0.001	21.53	0.001	4.47	0.000
72.23	0.003	70.83	0.003	66.10	0.002	75.10	0.003	52.34	0.002	57.25	0.003
34.11	0.002	65.84	0.003					20.66	0.001	16.52	0.001
373.76	0.018	552.58	0.025	391.18	0.014	428.31	0.014	354.35	0.014	269.74	0.012
44.92	0.002	13.81	0.001	1.74	0.000	1.71	0.000	10.87	0.000		
89.60	0.004	196.62	0.009	68.01	0.003	109.73	0.004	148.02	0.006	546.11	0.025
88.04	0.004	25.15	0.001	24.05	0.001	76.86	0.002	67.58	0.002	361.11	0.016
67.66	0.003	264.32	0.012	8.78	0.000	1,332.58	0.043	22.69	0.001	28.81	0.001
3.12	0.000	83.79	0.004	2,924.12	0.105	0.85	0.000	13.02	0.000	6.74	0.000
12.16	0.001	42.66	0.002	9.74	0.000	10.66	0.000	40.02	0.002	106.49	0.005
		87.87	0.004	84.46	0.003						
305.50	0.014	714.22	0.033	3,103.34	0.112	1,532.39	0.049	302.20	0.011	1,049.26	0.047
679.26	0.032	1,266.80	0.058	3,494.52	0.126	1,960.70	0.063	656.55	0.025	1,319.00	0.059
2,729.73	0.129	2,838.58	0.130	2,886.00	0.104	2,979.79	0.097	2,853.01	0.110	2,694.37	0.121
8,182.95	0.387	9,308.23	0.430	13,314.22	0.478	12,599.27	0.407	10,360.58	0.400	9,331.92	0.419
10,912.68	0.516	12,146.81	0.560	16,200.22	0.582	15,579.06	0.504	13,213.59	0.510	12,026.29	0.540
197.62	0.009	174.49	0.008	189.88	0.007	199.84	0.007	184.06	0.007	182.68	0.008
11,110.30	0.525	12,321.30	0.568	16,390.10	0.589	15,778.90	0.511	13,397.65	0.517	12,208.97	0.548
2,115,900		2,167,500		2,784,300		3,088,300		2,590,400		2,229,000	
3.269		3.14		3.16		3.058		3.306		3.168	
$2.19		$2.42		$2.24		$2.24		$2.24		$2.24	

graph, crossing gatemen, together with traffic expenses and general expenses.

Table II shows the cost of operation and maintenance of the Westville power station for the year 1910. This statement is subdivided under the general headings of operation and maintenance and under the further sub-headings of material and labor. The statement shows the total monthly cost as well as the cost in cents per kw-hr. for each item.

TABLE I

WEST JERSEY & SEASHORE RAILROAD

Electric train service

Passenger train statistics

Cost of operation in cents per car mile

Year 1909

	Repairs, Electric Equipment of Cars.	Repairs Passenger Cars.	Other Maintenance of Equipment Costs.	Electric Power at Car Shoes.	Yard Service Shifting Costs	Motormen	Trainmen.	Train Supplies and Expenses.	Total.	Other Expenses	Total Expenses.	Car Miles, Total.	Average Cars per Train.
January......	1.06	2.05	0.48	4.78	0.51	0.93	1.53	1.20	12.53	10.25	22.78	279,210	3.113
February.....	1.07	2.42	0.38	4.63	0.51	0.91	1.49	1.22	12.63	10.99	23.62	258,130	3.163
March........	1.18	1.97	0.35	4.99	0.52	0.99	1.65	1.18	12.83	10.17	23.00	279,193	3.092
April..........	1.26	2.03	0.25	4.43	0.46	0.89	1.40	0.61	11.32	9.14	20.46	317,963	3.483
May..........	0.84	1.73	0.26	3.98	0.44	0.88	1.45	0.45	10.03	9.18	19.21	318,006	3.482
June..........	0.40	0.68	0.31	3.58	0.25	0.86	1.41	0.42	7.91	9.35	17.26	339,294	3.530
July..........	0.33	0.44	0.12	2.82	0.20	0.80	1.25	0.40	6.36	6.95	13.31	478,203	3.660
August........	0.28	0.40	0.14	2.75	0.20	0.75	1.18	0.36	6.06	6.29	12.35	517,223	3.921
September....	0.43	0.67	0.14	2.75	0.25	0.83	1.32	0.42	6.81	6.87	13.68	428,571	3.584
October......	0.64	0.71	0.24	3.84	0.31	0.92	1.53	0.62	8.81	10.21	19.02	307,825	3.046
November....	0.52	0.39	0.29	3.85	0.29	0.95	1.70	0.82	8.81	9.30	18.15	291,816	3.327
December....	0.87	1.08	0.29	12.31	0 30	1.00	1.72	1.30	18.87	15.05	33.92	292,175	3.318
Avg..........	0.68	1.10	0.25	4.30	0.33	0.88	1.44	0.69	9.67	9.08	18.75	4,107,609	3.457

Year 1910

	Repairs, Electric Equipment of Cars.	Repairs Passenger Cars.	Other Maintenance of Equipment Costs.	Electric Power at Car Shoes.	Yard Service Shifting Costs	Motormen	Trainmen.	Train Supplies and Expenses.	Total.	Other Expenses	Total Expenses.	Car Miles, Total.	Average Cars per Train.
January......	0.86	1.03	0.67	4.59	0.46	0.96	1.64	2.24	12.45	7.22	19.67	292,523	3.169
February.....	0.79	1.78	0.33	5.38	0.50	0.97	1.48	1.07	12.30	12.44	24.74	262,488	3.137
March........	1.04	1.13	0.28	3.87	0.48	0.88	1.51	0.89	10.08	12.91	22.99	333,252	3.445
April..........	0.62	0.76	0.31	4.57	0.49	0.97	1.62	0.70	10.04	11.55	21.59	302,463	3.344
May..........	0.57	0.78	0.24	2.78	0.48	0.89	1.41	0.44	7.59	9.92	17.51	351,994	3.651
June..........	0.79	0.67	0.24	2.80	0.45	0.97	1.62	0.58	8.12	10.13	18.25	375,023	3.406
July..........	0.44	0.46	0.18	2.47	0.34	0.89	1.39	0.36	6.53	6.66	13.19	565,787	3.641
August........	0.29	0.57	0.15	2.48	0.33	0.85	1.38	0.37	6.42	5.62	12.04	594,852	3.811
September....	0.37	0.54	0.21	2.71	0.39	0.85	1.42	0.42	6.91	7.34	14.25	487,543	3.771
October......	0.73	1.19	0.28	3.05	0.47	0.91	1.69	0.52	8.84	12.34	21.18	339,789	3.564
November....	1.40	2.45	0.47	3.71	0.51	0.96	1.71	0.54	11.75	10.58	22.33	311,882	3.379
December....	0.63	1.94	0.21	3.93	0.51	0.93	1.71	0.74	10.60	12.13	22.73	334,936	3.494
Avg..........	0.66	1.01	0.27	3.33	0.43	0.91	1.52	0.67	8.80	9.39	18.19	4,552,532	3.518

The total net output from the station is also shown as well as the pounds of coal per kw-hr. and the cost of coal per ton of 2,000 lb.

Table III is given showing the cost of maintenance of the transmission system, which includes high-tension transmission, overhead trolley, third rail and running track bonding.

In connection with the maintenance cost of overhead trolley, it should be borne in mind that the trolley construction is of

TABLE III

WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE

Cost of maintenance of transmission systems

Year 1910

	High tension		Overhead trolley		Third rail		Running track bonding	
	Total	Per mile	Total	Per mile	Total	Per mile	Total	Per mile
January....	$142.96	$2.04	$690.84	$35.32	$492.96	$3.74	$26.67	$1.51
February..	409.74	5.85	266.38	13.62	580.80	4.41	562.82	3.75
March.....	198.62	2.84	381.28	19.49	495.55	3.76	39.26	0.26
April......	403.44	5.76	446.57	46.71	745.16	5.26	†30.24	0.20
May......	256.14	3.66	291.51	30.49	1,126.40	7.95	190.05	1.27
June......	123.21	1.76	864.62	90.44	957.42	6.75	312.08	2.08
July.......	167.90	2.40	393.62	41.17	818.29	5.77	494.79	3.30
August....	357.20	5.10	317.49	33.21	1,631.72	11.51	32.99	0.22
September.	506.51	7.26	389.73	40.77	838.87	5.92	202.05	1.35
October....	604.93	8.64	245.75	25.70	647.27	4.57	98.66	0.66
November.	171.58	2.45	363.35	38.01	1,062.98	7.50	189.83	1.26
December.	100.34	1.43	244.02	25.52	1,466.71	10.35	125.03	0.83
Total and avg. per mi. per mo....	$3,444.57	$4.10	$4,895.16	$36.70	$10,864.13	$6.46	$2,445.72	$1.36

†Credit for scrap 56.75

TABLE IV

WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE

Cost of operation and maintenance of substations

Year 1910

	Total for eight substations				
	Operation	Maintenance	Total	Cost per kw-hr.	Substation output kw-hr. 675 volts direct-current
January......	$1,573.82	$373.10	$1,946.92	$0.001136	1,655,800
February.....	1,601.78	147.39	1,749.17	0.001157	1,460,200
March........	1,618.16	174.27	1,792.43	0.001035	1,678,400
April.........	1,728.98	275.64	2,004.62	0.001251	1,554,900
May..........	1,760.46	370.91	2,131.37	0.001267	1,635,900
June..........	1,794.44	432.55	2,226.99	0.001310	1,655,600
July..........	2,006.97	317.62	2,324.59	0.001047	2,175,700
August........	1,751.03	194.13	1,945.16	0.000811	2,349,000
September....	1,776.14	903.45	2,679.59	0.001285	2,035,200
October.......	1,744.23	145.99	1,890.22	0.001069	1,712,100
November....	1,750.62	142.23	1,892.85	0.000986	1,860,100
December.....	1,745.68	130.02	1,875.70	0.000820	2,199,400
Year.........	$20,852.31	$3,607.30	$24,459.61	$0.001082	21,972,300

rigid span type and also that current is collected by a trolley wheel on each car of a train, the number of cars per train varying from two to seven, the average being about three.

Originally the ten mile line from Newfield to Millville was equipped with overhead trolley of the same construction as the present line. This trolley was replaced by third rail the latter part of March, 1910, hence the maintenance cost per mile in Table 3 is based on 19.55 miles to March, inclusive, and on 9.55 miles from that time on.

The operation and maintenance of substations for the year 1910 is shown in Table IV. This shows the cost of operation and maintenance of the eight substations during the year 1910, by month, as well as the cost per kw. hr. output per substation and the output in direct current at 675 volts.

DETENTIONS TO TRAIN SERVICE

A detailed statement of the detentions to electric train service occurring during the year 1909 is given in table No. VIII. The column headed "Number of detentions," means number of trains detained and is subdivided into totals and per cent of total. The column headed, "minutes detention", shows the train minutes of detention for each cause and is subdivided into the headings of totals and per cent of totals. The column headed "car miles per minute of detention", shows the total car miles per train minute of detention for each cause.

A further subdivision of the detentions due to train equipment shown under the general heading "motive power", is given in Tables IX and X the first being for the year 1909 and the second for the year 1910. This statement shows the detentions that occurred during each year by months and it may be well to say that the figure shown above the line represents the number of detentions, while the figure below the line represents the train minutes delay for that particular detention.

RENEWAL OF PARTS OF CAR EQUIPMENT

The number of renewals of the various parts of car equipment for the year 1909 is given by months in Table V and the same information for the year 1910 is given in Table VI.

The car mileage for 1909 being 4,106,765 and for 1910, 4,552,056, it is seen that the number of car miles per third rail shoe replaced in 1909 was 8068 and in 1910 was 4079, giving an average of about 6005 car miles per replacement. As each car is

TABLE V
WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE
RENEWAL OF PARTS OF CAR EQUIPMENT
1909

Part of equipment	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Third rail shoes replaced	42	38	51	42	12	10	39	59	28	71	62	55	509
Brake shoes replaced	388	237	353	423	304	435	536	592	689	476	402	462	5297
Trolley poles bent	3	1	14	8	9	12	12	15	10	10	3	11	108
Trolley poles broken	0	0	1	0	0	0	0	1	0	0	1	0	3
Trolley poles missing or replaced	0	1	0	0	0	0	0	0	0	0	4	0	5
Trolley wheels lost or replaced	24	23	25	19	27	2	36	17	38	13	11	24	259
Trolley retriever dogs broken	0	0	0	0	0	0	0	0	0	0	0	0	0
Trolley harps broken or replaced	11	7	5	2	5	3	6	6	5	1	0	0	51
800 ampere shoe fuses blown	264	198	226	193	180	113	101	125	69	138	197	279	2081
800 ampere trolley fuses blown	52	33	34	40	15	26	45	101	37	53	46	36	518
800 ampere bus fuses blown	15	10	17	9	11	6	17	14	11	21	12	59	202
25 ampere controller fuses blown	5	7	6	6	2	0	0	1	2	6	5	11	51
20 ampere No. 2 heater fuses blown	15	18	9	24	4	7	0	0	2	23	16	26	144
10 ampere No. 1 heater and comp. fuses blown	21	27	25	18	7	2	1	9	24	28	27	35	224
5 ampere cab heater fuses blown	0	1	0	0	0	0	0	0	1	0	0	4	6
4 ampere control cable fuses blown	3	4	11	1	0	1	1	2	7	1	1	2	34
3 ampere headlight fuses blown	4	0	1	3	2	0	2	3	5	1	0	13	34
1 ampere car light fuses blown	2	1	0	4	9	6	5	8	19	7	3	11	75
50 c.p. headlights burned out	20	18	10	18	11	22	40	40	36	24	16	16	271
50 c.p. headlights missing	1	1	1	3	1	4	1	0	3	1	0	1	17
16 c.p. lamps burned out	188	148	180	182	140	103	129	153	163	141	156	169	1862
16 c.p. lamps missing	41	45	42	14	42	26	15	21	33	18	28	51	376
16 c.p. lamps broken	9	18	4	18	5	22	6	7	6	9	7	14	125
Gauge lamps replaced	24	18	14	10	12	5	4	12	4	5	11	10	129

TABLE VI
WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE
RENEWAL OF PARTS OF CAR EQUIPMENT
1910

Parts of equipment	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Third rail shoes replaced	198	125	157	43	27	58	26	41	67	54	73	60	933
Brake shoes replaced	425	454	511	469	511	570	675	780	531	416	444	514	6300
Trolley poles bent	4	6	12	12	5	9	8	12	16	2	1	2	89
Trolley poles broken	3	3	1	3	1	0	3	0	3	1	0	0	18
Trolley poles missing or replaced	2	4	0	1	0	1	1	4	3	1	0	4	21
Trolley wheels lost or replaced	19	2	13	9	10	19	18	5	13	3	1	12	124
Trolley retriever dogs broken	0	0	0	0	0	0	0	0	0	0	0	0	0
Trolley harps broken or replaced	2	4	1	4	0	4	2	1	3	2	0	2	24
800 ampere shoe fuses blown	186	199	284	173	178	248	229	304	287	210	197	303	2798
800 ampere trolley fuses blown	56	55	51	23	22	48	107	75	70	32	17	19	575
600 ampere bus fuses blown	48	11	25	29	17	29	19	22	22	6	3	17	248
25 ampere controller fuses blown	14	8	4	6	1	2	4	0	0	1	20	5	65
20 ampere No. 2 heater fuses blown	17	13	19	7	0	2	0	0	0	2	33	13	106
10 ampere No. 1 heater and comp. fuses blown	28	31	21	19	7	9	2	1	3	5	27	25	178
5 ampere cab heater fuses blown	0	14	0	0	0	0	0	0	0	0	0	1	15
4 ampere contrl. cable fuses blown	0	0	2	0	0	1	6	5	6	2	4	3	29
2 ampere headlight fuses blown	9	24	4	6	3	2	1	1	7	5	3	17	82
1 ampere car light fuses blown	4	16	21	3	3	6	2	2	6	3	3	7	76
50 c.p. headlights burned out	25	14	3	18	16	14	21	13	18	14	12	9	177
50 c.p. headlights missing	17	21	1	3	2	3	3	2	6	0	0	6	64
16 c.p. lamps burned out	193	211	150	125	93	76	96	100	135	163	157	182	1699
16 c.p. lamps missing	72	59	64	50	49	45	25	26	27	39	54	67	577
16 c.p. lamps broken	19	20	7	6	0	2	5	4	9	5	3	3	83
Gauge lamps replaced	27	17	6	13	9	8	10	8	7	1	4	0	110

equipped with four shoes this gives an average life of 24,020 miles per shoe.

Likewise the number of car miles per brake shoe was 775 in 1909 and 722 in 1910 or an average of about 747 car miles per replacement. The average life of each brake shoe is therefore about 5976 miles.

The number of replacements of the remaining items is governed rather by special occurrences than by mileage, with the exception of the lamps, the average life of which is not readily obtainable owing to incomplete data concerning number of hours burned.

A statement is also included showing the breakage of gears and pinions by month for the years 1909 and 1910. This will be found by reference to Table VII.

TABLE VII

WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE

Gear and pinion breakages

	1909	1910
January	4	1
February	3	1
March	5	3
April	2	1
May	1	5
June	0	1
July	0	0
August	1	0
September	1	0
October	2	0
November	0	0
December	2	1
Total	21	13

Table XI shows, by months, for the years 1907, 1908, 1909 and 1910 certain general power data, which are included as being of some interest. This statement, shows the kw-hr. output from power station, the cost in mills per kw-hr. output, pounds of coal per kw-hr., and the efficiency of transmission and conversion from the alternating current bus in the power station to direct current bus in substations.

An improvement will be noted in the reduction of cost of power, as well as a reduction in coal consumption per kilowatt hour. The most marked improvement, however, will be noted in efficiency of transmission and conversion, which is accounted for by the fact that the operation of the substations is followed up with care so as to minimize the idle operation of rotaries.

TABLE VIII
WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE
Detentions
Year 1909

Causes	Train detentions, number, time and per cent for various causes				
	Number of detentions		Minutes detention		
	Total	Per cent of total	Total	Per cent of total	Car miles per minute detention
Transportation.					
Boat connection	51	0.553	180	0.403	22,815.36
Baggage, express and mail	1898	20.575	8373	18.749	490.47
Heavy travel	1232	13.355	4612	10.328	890.45
Collecting tickets	72	0.781	334	0.748	12,295.70
Train connections	977	10.591	5517	12.354	744.38
Traffic ahead	1723	18.677	7842	17.561	523.68
Held at signal	1390	15.068	4767	10.675	861.50
Stops on order	73	0.791	165	0.369	24,889.49
Fast schedule	34	0.368	57	0.128	72,048.50
Picking up and cutting off cars	411	4.455	1312	2.938	3,130.15
Fog	41	0.444	127	0.284	32,336.73
Signal failure	208	2.255	860	1.926	4,775.31
Accidents	26	0.282	261	0.584	15,734.73
Obstructions	33	0.358	194	0.434	21,168.89
Miscellaneous	283	3.068	1427	3.196	2,877.90
Total transportation	4852	91.621	36028	80.677	113.98
Motive power.					
Power house trouble	15	0.163	69	0.155	59,518.30
High tension line trouble	14	0.152	81	0.181	50,700.80
Lightning	12	0.130	47	0.105	87,377.90
Overloads in substations	11	0.119	61	0.137	67,324.00
Third rail shorts	3	0.032	14	0.031	293,340.40
Third rail out of place	1	0.011	8	0.019	513,345.13
Third rail anchor on fire	1	0.011	5	0.011	821,353.00
Third rail protection out of place	1	0.011	1	0.002	4,106,765.00
Trolley wire trouble	253	2.742	1920	4.299	2,138.94
Train equipment	237	2.569	1568	3.511	2,619.11
Total motive power	548	5.940	3774	8.451	1,088.17
Weather Conditions.					
Snow, head winds, wet rail	178	1.929	4043	9.054	1,015.77
Sleet on third rail	47	0.510	812	1.818	5,057.59
Total weather condition	225	2.439	4855	10.872	845.88
Grand total	9225	100.00	44657	100.00	91.96

Total car mileage	4,106,765
Car miles per detention	445.18
Car miles per minute of detention	91.96

TABLE XI
WEST JERSEY & SEASHORE RAILROAD ELECTRIC TRAIN SERVICE

General power data

	1907				1908			
	Alternating Current kw-hr Power Station Output	Cost in Mills per Kw-hr. Output	Lb. of Coal Kw-hr. Output	Efficiency Power Sta. Bus to Substation Bus	Alternating Current Kw-hr. Power Station Output	Cost in Mills per Kw-hr. Output	Lb. of Coal Kw-hr. Output	Efficiency Power Sta. Bus to Substation Bus
January......	1,911,600	8.83	3.91	72.6	2,009,600	6.10	3.49	73.3
February.....	1,691,500	7.95	3.63	74.5	1,913,100	6.35	3.55	73.6
March.......	1,583,000	7.76	3.96	71.5	1,873,300	6.17	3.46	72 3
April.........	1,464,300	7.43	3.95	74.0	1,836,200	5.86	3.45	71.8
May..........	1,400,400	6.81	3.53	72.1	1,744,900	6.06	3.40	69.6
June..........	1,395,700	7.65	3.98	70.6	1,707,500	5.91	3.52	74.8
July..........	1,938,100	6.05	3.65	71.6	2,104,300	5.43	3.37	75.6
August.......	2,082,000	6.00	3.43	71.6	2,268,000	5.43	3.18	75.8
September ...	1,855,300	6.07	3.46	71.7	1,849,200	5 76	3.18	74.7
October.......	1,849,800	5.99	3.53	82.8	1,786,700	5.78	3.25	72.8
November....	1,893,600	5.86	3.51	71.3	1,802,000	5.78	3.35	74.7
December....	2,053,600	6.00	3.51	72.5	1,993,000	5.80	3.25	76.2
Av. for year...	1,759,900	6.80	3.67	72.2	1,907,300	5.92	3.37	73.8
	1909				1910			
January......	1,959,700	5.67	3.23	76.1	2,131,000	5.15	3.31	81.8
February.....	1,756,500	5.71	3.25	76.1	1,865,300	5.73	3.46	82.4
March.......	1,903,600	6.04	3.33	76.1	2,168,600	5.42	3.27	81.3
April.........	1,869,300	5.90	3.27	75.0	2,031,400	5.62	3.22	80.1
May..........	1,788,800	5.65	3.26	75.5	2,115,900	5.25	3.27	79.5
June..........	1,749,200	5.77	3.22	77.7	2,167,500	5.68	3.14	80.3
July..........	2,426,000	5.21	3.25	78.0	2,784,300	5.88	3.16	82.5
August.......	2,324,400	5.27	3.34	81.5	3,088,300	5.11	3.06	80.7
September....	2,056,100	5.28	3.34	80.3	2,590,400	5.17	3.31	82.9
October,......	1,836,600	5.40	3.27	80.1	2,229,000	5.48	3.17	80.8
November....	1,869,500	5.49	3.41	80.7	2,381,500	5.19	3.29	81.9
December....	2,154,800	5.42	3.41	81.0	2,759,300	5.31	3.36	83.4
Av. for year..	1,962,600	5.55	3.30	78.4	2,350,400	5.42	3.25	81.6

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REPORT OF DETENTIONS TO PASSENGER TRAINS DUE

Date	MASTER CONTROL								MOTOR CONTROL												MOTORS											AIR					
	Switches Defective				Train Cable Jumper		Relay			Fuses Blown			Bus Line								Armature											Compressor			Brakes		
	Master control	Circuit breaker	Control fuse blown	Train cable	Grounded	Loose	Current limit	Potential	Controller	Main	Shoe	Trolley	Bus	Grounded	Loose jumper	Circuit breaker defective	Reverser defective	Contactors defective	Resistance grids	Snow in contactor box	Grounded	Short circuited	Open circuited	Fields defective	Leads defective	Flash-overs	Brush holders	Broken gears	Loose gears	Broken pinions		Fuse blown	Governor defective	Pump defective	Fail to release	Equalize	Defective rigging
January	..	..	..	..	1	..	..	..	1	..	4	2	..	..	..	..	..	3	..	1	..	..	..	..	..	..	..	1	..	5	..	..	..	..	..	..	..
	..	..	..	..	9	..	..	..	1	..	100	6	..	..	..	..	..	8	..	5	..	..	..	..	..	..	..	2	..	56	..	..	..	..	..	..	..
February	..	..	2	..	..	..	..	..	1	..	1	..	..	..	..	..	..	3	..	..	2	..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	1
	..	..	7	..	..	..	..	..	14	..	9	..	..	..	..	..	..	15	..	..	3	..	..	..	..	..	..	..	..	..	..	..	2	..	..	..	8
March	..	..	..	..	1	..	1	..	..	..	2	..	2	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	1	..	..
	..	..	..	..	38	..	3	..	..	..	37	..	5	..	..	..	2	..	..	..	..	..	..	..	..	..	..	..	..	4	..	..	..	..	4	..	..
April	..	..	..	..	..	..	1	..	1	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	3	..	..	..	..	..	..	1
	..	..	..	..	..	..	2	..	2	..	..	..	..	..	..	..	4	..	..	..	..	..	..	..	..	..	..	..	..	34	..	..	..	..	..	..	2
May	..	..	..	..	..	..	..	..	2	..	..	..	..	..	..	..	1	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
	..	..	..	..	..	..	..	..	3	..	..	..	..	..	..	..	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
June	..	..	..	2	..	..	..	..	2	..	..	..	1	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1	..	..
	..	..	..	14	..	..	..	..	16	..	..	..	4	..	..	..	..	5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	2	..	..
July	..	..	1	..	..	1	..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	1	..	..	1	..	1
	..	..	4	..	..	6	..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	7	..	..	..	4	..	..	..	1	..	..	2	..	4
August	..	..	..	..	..	..	..	..	..	..	..	2	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	1
	..	..	..	..	..	..	..	..	..	..	..	6	..	..	..	..	..	3	..	..	..	..	..	..	..	..	..	..	..	..	..	4	..	..	..	..	3
September	..	..	1	..	..	..	1	..	..	..	..	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	2	..	..	..	..	..	..	..
	..	..	2	..	..	..	1	..	..	..	..	8	14	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	32	..	..	..	..	..	..	..
October	..	..	..	..	..	..	2	..	..	..	..	3	..	..	..	..	..	..	1	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
	..	..	..	..	..	..	4	..	..	..	..	28	..	..	..	..	..	..	3	5*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	4
November	..	..	..	..	..	3	..	1	..	..	..	2	..	..	..	..	..	2	..	..	..	..	..	..	..	..	..	..	..	..	..	1	..	..	1	..	..
	..	..	..	..	..	17	..	2	..	..	..	11	..	..	..	..	..	7	..	..	..	..	..	..	..	..	..	..	..	..	..	4	..	..	2	..	..
December	..	..	..	2	..	2	..	..	1	..	..	..	..	1	..	..	3	3	..	..	1	..	..	..	..	..	..	..	..	2	..	..	..	..	..	..	..
	..	..	..	3	..	24	..	..	4	..	..	..	..	4	..	..	13	17	..	..	11	..	..	..	..	..	..	..	..	8	..	..	..	..	..	..	..
Total	..	..	4	4	2	6	5	1	8	..	7	11	5	1	..	..	6	15	1	3	3	..	..	1	..	..	..	2	..	13	..	3	1	..	4	..	5
	..	..	13	17	47	47	10	2	40	..	146	59	23	4	..	..	21	58	3	10	14	..	..	7	..	..	..	6	..	134	..	9	2	..	10	..	21

*Dirt on interlocks.

TABLE IX
NIA RAILROAD COMPANY
SHORE RAILROAD COMPANY
TRAIN SERVICE
UE TO FAILURES OF TRAIN EQUIPMENT FOR YEAR 1909

(West of [illegible])

R BRAKES												TROLLEY		HEADLIGHT			HOT BEARINGS			COUPLERS		TRUCKS						CAR MILES		
	Hose				Valve																				Misc.					
Defective rigging	Burst	Defective	Pipes broken or defective	Feed	Triple	Brake	Drain cock	Emergency attachment	Sleet on third rail	Poles grounded	Wheels defective	Ropes broken	Retriever	Fuse blown	Burnt out	Armature	Motor axle	Journal	Compressor motor	Broken	Defective	Contact shoe	Shoe beam	Whistle defective	Trolley wire	Total failures	Minutes lost	Total	Per detention	Per [illegible]
..	..	..	..	..	..	..	..	..	35	1	..	..	..	..	2	..	..	..	4	..	..	..	..	2	4					
..	..	..	..	..	..	..	..	..	742	4	..	..	..	..	9	..	..	..	71	..	..	..	..	17	11	26	204	279,210	10,739	[illegible]
1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	2	..	..	..	..	..	..	1	..	..	..					
8	..	..	..	..	..	..	..	..	..	..	..	..	..	..	8	..	..	..	..	..	..	2	..	..	..	15	71	257,981	17,199	3,633
..	..	..	..	..	..	..	..	1	..	..	..	1	2	..	1	..	..	1	..	..	..	5	..	1	6					
..	..	..	..	..	..	..	..	22	..	..	..	6	3	..	3	..	..	36	..	..	..	55	..	2	11	23	225	279,198	12,139	1,241
1	1	1	1	..	..	..	..	1	..	..	..	..	..	..	..	..	..	3	..	..	..	1	..	..	3					
2	2	7	4	..	..	..	..	1	..	..	..	..	..	..	..	..	..	35	..	..	..	1	..	..	13	19	105	317,763	16,724	3,026
..	..	..	..	..	..	..	..	..	..	1	1	..	..	..	..	..	..	2	..	..	..	2	..	..	10					
..	..	..	..	..	..	..	..	..	..	5	1	..	..	..	..	..	..	12	..	..	..	23	..	..	[illegible]	12	40	318,006	26,501	7,950
..	..	..	..	..	..	..	..	..	..	..	..	..	1	..	5	..	..	2	..	..	..	..	..	5	17					
..	..	..	..	..	..	..	..	..	..	..	..	..	3	..	13	..	..	19	..	..	..	..	..	11	45	20	87	339,024	16,951	3,897
1	..	..	2	..	..	..	..	..	..	..	..	..	..	..	5	..	..	3	..	..	..	..	..	1	24					
4	..	..	6	..	..	..	..	..	..	..	..	..	..	..	23	..	..	26	..	..	..	..	..	3	397	19	87	477,968	25,156	5,494
1	..	..	..	..	1	..	..	..	..	..	..	..	..	..	4	..	2	2	..	..	..	1	..	2	70					
3	..	..	..	..	9	..	..	..	..	..	..	..	..	..	16	..	8	24	..	..	..	3	..	14	[illegible]	17	90	517,228	30,425	5,747
..	..	..	..	..	..	..	..	..	..	..	..	1	..	1	9	..	2	4	..	..	..	..	..	1	92					
..	..	..	..	..	..	..	..	..	..	..	..	3	..	1	56	..	5	82	..	..	..	..	..	1	712	26	205	428,571	16,484	2,091
1	..	..	..	..	..	..	..	..	..	..	..	..	1	..	2	..	..	4	..	..	..	..	1	1	19					
4	..	..	..	..	..	..	..	..	..	..	..	..	4	..	7	..	..	61	..	..	..	..	3	3	[illegible]	18	122	307,825	17,101	2,528
..	..	..	..	..	..	..	..	..	10	..	..	1	..	..	1	..	..	2	..	..	..	..	..	1	13					
..	..	..	..	..	..	..	..	..	48	..	..	2	..	..	3	..	..	13	..	..	..	..	..	2	[illegible]	15	63	291,816	19,454	4,632
..	..	..	..	..	..	..	..	..	2	..	..	1	1	2	3	..	..	1	..	..	..	..	1	3	18					
..	..	..	..	..	..	..	..	..	22	..	..	1	3	18	21	..	..	10	..	..	..	..	10	23	275	27	170	292,175	10,821	1,719
5	1	1	3	..	1	..	..	2	47	2	1	4	5	3	24	..	4	24	4	..	..	10	2	17	[illegible]					
21	2	7	10	..	9	..	..	23	812	9	1	12	13	19	150	..	13	318	71	..	..	84	13	76	1980	237	1508	4,106,705	17,328	2,819

(Figures in heavy type not included in totals.)

Date	MASTER CONTROL									MOTOR CONTROL													
	Switches Defective				Train Cable Jumper		Relay			Fuses Blown				Bus Line							Armature		
	Master control	Circuit breaker	Control fuse blown	Train cable	Grounded	Loose	Current limit	Potential	Controller	Main	Shoe	Trolley	Bus	Grounded	Loose jumper	Circuit breaker defective	Reverser defective	Contactors defective	Resistance grids	Defective wiring	Grounded	Broken shaft	Open circuited
January	..	..	..	..	1	..	..	..	..	1	..	2	..	1	1	..	2	..	..	..	..	..	..
	..	..	..	..	16	..	..	..	..	1	..	10	..	5	2	..	8	..	..	..	..	..	..
February	..	..	..	..	3	..	..	..	1	..	..	..	2	..	..	..	1	3	..	..	..	..	..
	..	..	..	..	11	..	..	..	3	..	..	..	13	..	..	..	4	18	..	..	..	..	..
March	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	2	..	..	..	..	..
	..	..	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	11	..	..	..	..	..
April	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	..	..	1	..	..	..	1	..
	..	..	2	..	..	..	2	..	..	..	..	..	..	..	..	..	..	10	..	..	..	14	..
May	..	..	1	..	1	1	2	..	..	..	1	..	..	..	..	..	..	2	..	..	..	..	..
	..	..	2	..	4	6	11	..	..	..	2	..	..	..	..	..	..	5	..	..	..	..	..
June	..	..	1	1	..	..	1	..	..	..	..	1	..	..	..	1	1	..	..	..	..	..	..
	..	..	2	12	..	..	2	..	..	..	..	5	..	..	..	4	3	..	..	..	..	..	..
July	..	..	..	..	..	1	..	..	..	..	..	7	4	..	..	2	1	4	..	..	1	..	..
	..	..	..	..	..	17	..	..	..	..	..	33	26	..	..	3	1	8	..	..	3	..	..
August	..	..	..	1	..	..	2	1	..	..	..	2	..	..	..	..	..	5	..	..	5	..	..
	..	..	..	1	..	..	6	2	..	..	..	9	..	..	..	..	..	19	..	..	24	..	..
September	..	..	1	..	..	..	..	..	..	1	1	1	..	..	1	..	1	1	..	..	..	..	..
	..	..	11	..	..	..	..	..	..	2	14	6	..	..	4	..	4	4	..	..	..	..	..
October	..	..	2	..	2	..	3	..	..	..	..	1	..	..	..	..	..	5	..	..	2	..	..
	..	..	3	..	11	..	4	..	..	..	..	3	..	..	..	..	..	21	..	..	5	..	..
November	..	..	..	1	..	..	2	..	..	..	..	2	2	..	..	2	2	2	..	..	1	..	..
	..	..	..	4	..	..	6	..	..	..	..	3	13	..	..	7	9	4	..	..	2	..	..
December	..	..	..	..	..	2	1	1	..	..	..	2	..	..	1	3	..	7	..	1	..	1	..
	..	..	..	..	..	10	2	2	..	..	..	5	..	..	2	11	..	21	..	5	..	2	..
Year	..	..	7	3	7	4	12	2	1	2	2	18	8	1	3	8	8	32	..	1	9	2	..
	..	..	22	17	42	33	33	4	3	3	16	74	52	5	8	25	29	121	..	5	34	16	..

STATEMENT NO. X
PENNSYLVANIA RAILROAD COMPANY
WEST JERSEY & SEASHORE RAILROAD COMPANY
ELECTRIC TRAIN SERVICE
TENTIONS TO PASSENGER TRAINS DUE TO FAILURES OF TRAIN EQUIPMENT FOR YEAR 1910

			AIR BRAKES															TROLLEY				HEADLIGHT		HOT BEARINGS				
			Compressor Brakes						Hose			Valves																
Loose gears	Broken pinions	Sleet on third rail	Fuse blown	Governor defective	Pump defective	Fail to release	Equalize	Defective rigging	Burst	Defective	Pipes broken or defective	Feed	Triple	Brake	Trolley pole raceways	Emergency attachment	Trolley poles defective	Poles lost	Wheels defective	Ropes broken	Retriever	Fuse blown	Burnt out	Armature	Motor axle	Journal	Compressor motor	Low pilot
..	..	**42**	..	..	..	..	..	1	..	1	..	..	..	..	..	..	..	1	2	1	1	..	5	..	1	..	..	..
..	..	**1637**	..	..	..	..	..	13	..	2	..	..	..	..	..	..	..	4	9	2	2	..	37	..	1	..	..	..
..	..	..	..	..	..	1	..	4	..	..	..	..	2	..	..	..	..	..	..	2	1	2	2	..	..	1	..	..
..	..	..	..	..	..	7	..	26	..	..	..	..	4	..	..	..	..	..	..	10	6	9	5	..	..	7	..	..
..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	6	..	..	..	..	..	2	..	1	12	..	..
..	..	..	..	..	..	3	..	..	..	..	..	..	..	..	..	..	19	..	..	..	..	..	15	..	10	196	..	..
..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	7	..	..	..	..	..	..	..	3	..	..	2	..	..
..	..	..	..	..	..	3	..	..	..	..	..	..	..	..	21	..	..	..	..	..	..	..	6	..	..	21	..	..
..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	3	..	..	..	..	..	..	..	2	..	..	3	..	..
..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	4	..	..	..	..	..	..	..	4	..	..	18	..	..
..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	3	..	..	..	..	1	..	..	2	..	1	2	..	..
..	..	..	..	..	..	..	..	..	..	..	5	..	..	..	7	..	..	..	..	9	..	..	8	..	2	18	..	..
..	..	..	..	..	..	..	1	..	..	..	1	..	..	..	2	..	..	..	..	3	..	..	3	..	1	2	..	1
..	..	..	..	..	..	..	11	..	..	..	17	..	..	..	4	..	..	..	..	13	..	..	9	..	5	17	..	[illegible]
..	..	..	..	..	..	1	..	1	..	..	..	..	1	..	3	..	..	..	..	2	1	1	5	..	1	4	..	..
..	..	..	..	..	..	6	..	6	..	..	..	..	3	..	7	..	..	..	..	7	12	2	20	..	3	67	..	..
..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	1	..	1	2	..	1	4	..	..
..	..	..	..	..	..	..	..	28	..	..	..	..	..	..	..	..	..	..	..	4	..	6	3	..	12	58	..	..
..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1	..	2	..	..
..	..	..	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	3	..	12	..	..
..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	1	..	..	3	..	..	2	..	..
..	..	..	..	..	..	..	..	..	6	..	..	..	..	..	..	..	..	..	..	3	..	..	9	..	..	10	..	..
..	..	**18**	..	..	2	1	..	..	..	..	1	..	..	..	..	..	..	1	..	..	..	4	10	..	1	1	..	..
..	..	**225**	..	..	10	3	..	..	..	..	14	..	..	..	..	..	..	2	..	..	..	18	40	..	2	11	..	..
..	..	**60**	1	..	2	5	1	7	1	1	3	..	3	..	18	..	6	2	2	12	3	8	30	1	7	35	..	1
..	..	**863**	2	..	10	22	11	73	6	2	36	..	7	..	43	..	19	6	9	48	20	35	156	3	35	435	..	4

(Figures in heavy type not included in totals).

A paper presented at the 260th Meeting of the American Institute of Electrical Engineers, Toronto, Can., April 7, 1911, and discussed at the 28th Annual Convention, Chicago, June 28, 1911.

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ELECTRIFICATION ANALYZED, AND ITS PRACTICAL APPLICATION TO TRUNK LINE ROADS, INCLUSIVE OF FREIGHT AND PASSENGER OPERATION

BY WILLIAM S. MURRAY

Succinctly, the object of this paper is to place before the practical engineer and railroad man the facts concerning *trunk line electrification*, and bring home to him the simple truth that it can be treated in a class of its own; practically no exceptions existing therefrom. I would recommend that we be wary of the old expression so often repeated—"Every situation is a study in itself", and see if we cannot recognize a standard that will apply to all. In this connection I venture the opinion that there is no trunk line situation that exists to-day, but what there is a construction drawing in the New Haven engineering files that would have immediate application. No one can extract any individual credit for this fact; it is entirely due to the system itself, as it possesses the required elements of simplicity and flexibility. The religion of this paper is to preach the doctrine of universal use of single-phase current on trunk line roads inclusive of suburban and terminal territory, as applied to freight and passenger operation, and I offer for consideration the standardization of 11,000 volts on the contact wire and a system frequency of 25 cycles. In suggesting 11,000 volts on the contact wire, this is advocated for application on railroad right-of-way which may be adjacent to foreign road territory to permit of one company's equipment operating upon the right-of-way of another. This voltage is recommended as a minimum potential; it being recognized that there is no objection to a higher voltage on other lines individual to themselves where transmission economy can be obtained by the use of the higher voltage.

In recommending 25 cycles as standard for single-phase electrification, this is not so much based upon the successful use of this frequency on the New Haven road, as upon my belief that the future will undoubtedly see single-phase locomotive induction motors and probably single-phase current received at the terminals of the locomotive and transformed into direct current without the use of any rotating element within the locomotive. If 15 cycles, as some have been prone to recommend of late years, be elected as a standard frequency, such a frequency would handicap, if not eliminate, the opportunity of obtaining one of these two highly desirable alternatives entirely within reach by the use of 25 cycles.

We have made electrification in its various forms work. We can now make it pay. The only possible way that electrification can be made to pay is by electing such a system, the yearly operating cost of which, inclusive of its maintenance charges, subtracted from the yearly cost of the steam system it replaces, leaves a figure which represents a little more than the interest on the capital investment required for the installation of the electrical system. When the board of directors of a railroad company pass favorably upon an appropriation of several millions of dollars to purchase power houses at, say, a million dollars apiece, locomotives at $30,000 apiece and line construction at $25,000 or $30,000 a mile for a four-track system, it is not an unfair question for that board of directors (who, while they may be interested in eliminating the smoke and dirt incident to the original system replaced, and be glad to have the assurance of the electrical engineer that the time of switching movement of the railroad's equipments both in yards, terminal property and main line have been reduced) to ask for a closer analysis than this, and also ask for some specific explanation as to the return each year of a percentage of some of the dollars spent.

In the generosity of his heart, the practical railroad man has looked with some commiseration, some kindness and lately with some real interest upon those electrical engineers who are truly endeavoring, while engrossed in the principles of their own electrical art, not to forget in their studies to take into consideration the principles now of such long standing that have placed the art of steam railroading on its present sound basis.

With that in mind there follows in this paper a series of studies of a steam locomotive as it appears in its four classes, on a typical trunk line property. The whole problem of electrification, if viewed from the point of whether it is to pay, settles down to how much it costs to produce the necessary tractive effort required in

1. The passenger express locomotive;
2. The passenger local locomotive;
3. The freight road engine;
4. The freight switch engine;

together with such other costs incident to the electrical system.

The writer, during the past four years, has had the opportunity of studying these four classes of steam locomotives. The old railroad man when he reads over these statistical records will recognize the results. The electrical man, after he has read them, must realize that to make his electrification pay he must be able to reproduce the four classes of steam tractive efforts by electricity, with a total investment, the interest on which must be carried by the economies to be effected over steam operation.

THE STEAM PASSENGER LOCOMOTIVE

In a discussion of the paper presented before the American Institute of Electrical Engineers by Messrs. Stillwell and Putnam on January 25, 1907, the writer presented a tabulated set of figures with reference to the fuel required for the operation of steam passenger and freight locomotives, and the yearly cost of their maintenance and repairs.

Briefly quoting from that discussion, TRANSACTIONS A.I.E.E., Vol. XXVI, page 146, and with reference to the tables 1 and 2 there presented, showing the relation between coal consumption and ton-miles, the following statement is made: "An interesting and valuable query is—What fraction of a pound of coal is consumed in producing a ton-mile in any one of the above services? Tables 2 and 3, following, show that it takes 0.169 lb. of coal, 0.194 lb. of coal and 0.335 lb. of coal to produce a ton-mile in freight, express passenger and express local passenger service, respectively." In an effort to condense as much as possible the discussion, and confine the remarks to the results obtained, the writer omitted the presentation of the actual data from which the results were obtained; having in mind that later, and at a more opportune time, this data would be of interest. A very fair express and local trunk line service is offered in the trains of these respective classes between New Haven and New York City; and, as explained in the discussion previously referred to, a month was devoted to the study of the capacity of engines required and the coal consumed in such services over the 61.5 miles of route between New Haven and Woodlawn, N. Y., (east and west runs). In Figs. 1, 2, 3, 4 and 5, herewith, is given information with reference to average cut-off, boiler pressure, water consumption, indicated horse power and grade—all referred to stations along the route and supplemented by a synopsis of the general engine and train conditions which are inclusive of train schedule, weights, cylinder and wheel sizes, etc.

These data were secured for express operation, and the manner in which the tests were conducted is covered in TRANSACTIONS A.I.E.E., Vol. XXVI, page 146.

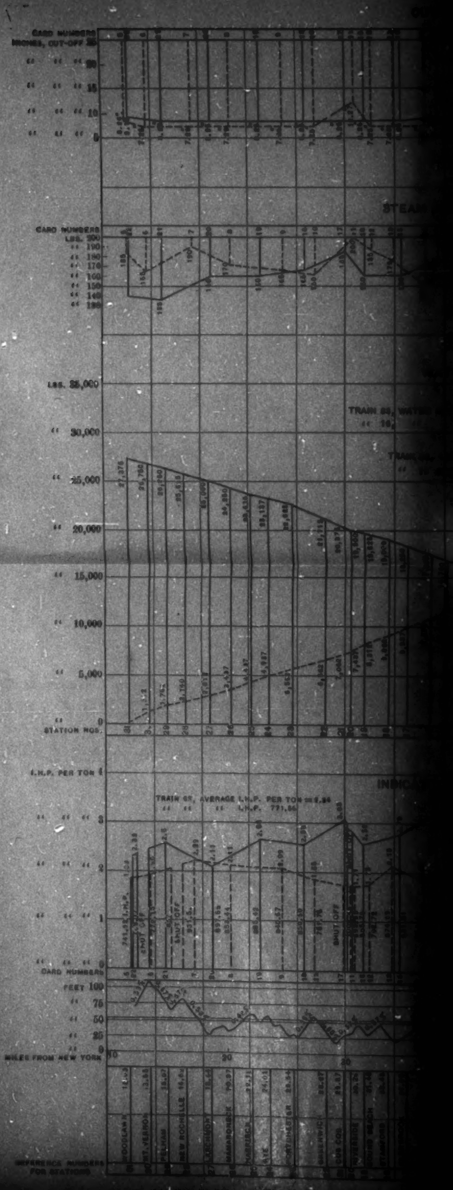
Figs. 6, 7, 8, 9 and 10, following, cover similar data for the steam local operation between New Haven and Woodlawn (east and west runs).

Figs. 11 and 12 give the respective averages of the aforegoing five tests, each for the express and local operation. The ten runs are presented, first, as a record of individual runs, and second, to show how very closely the tests checked upon themselves. As Figs. 11 and 12 are the summation and average of all other tests, the results plotted thereon can be used as references, rather than any data on Figs. 1 to 10, inclusive.

Space required for other matters does not permit a generous amount of discussion of these steam locomotive statistics. They present, perhaps, some reassuring evidence of our effort to become intimately acquainted with the problem the steam engineer had solved before the electrical engineer assimilated it for betterment. The writer would have liked to have covered the investigation more completely by a more exhaustive study of the track resistance, using trains of varying weight. Time, however, in those days was ever the essence of the contract, and the writer knew that the choice of train weights slightly below the average conditions would bring constants for ton-mile energy consumption at rates higher, and thus safer for reference in settling electrical capacities; and also knew that the future would offer a better opportunity to study the resistance problem by electric rather than steam locomotives. The two data most interesting to the writer in these plotted charts is the indication of the size of locomotive required to accomplish the

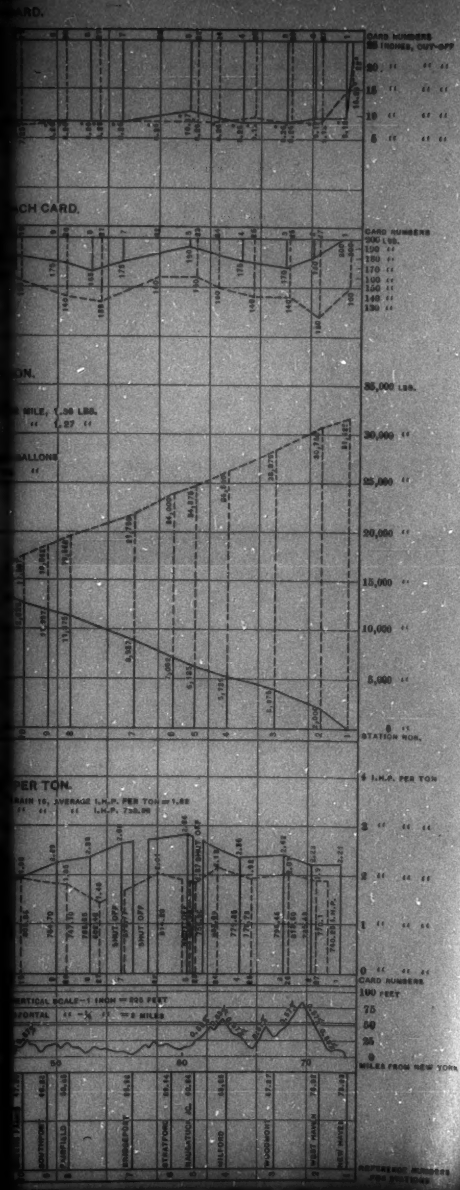
Wt. of train with engine [illegible]
5 cars in train.
Schedule time 1 hour, 13 min.
Actual time 1 hour, 15 min., 50 sec.

Working
Weight
Weight
Tank



232,000 lb.

Weight of train with engine [illegible] tons.
5 cars in train.
Schedule time 1 hour, 15 min.
Actual time 1 hour, 15 min., 40 sec.



Loc

Train 63, Sept. 21, 1905.
Shown by full lines.
Weight of train with engine, 329.73 tons.
5 cars in train.
Schedule time—1 hour, 12 min.
Actual time—1 hour, 12 min., 20 sec.

Engine 1310.
Size cylinder
Size wheel 78"
Working pres
Weight on dri
Weight of engi
Type, Americ
Tank capacity,

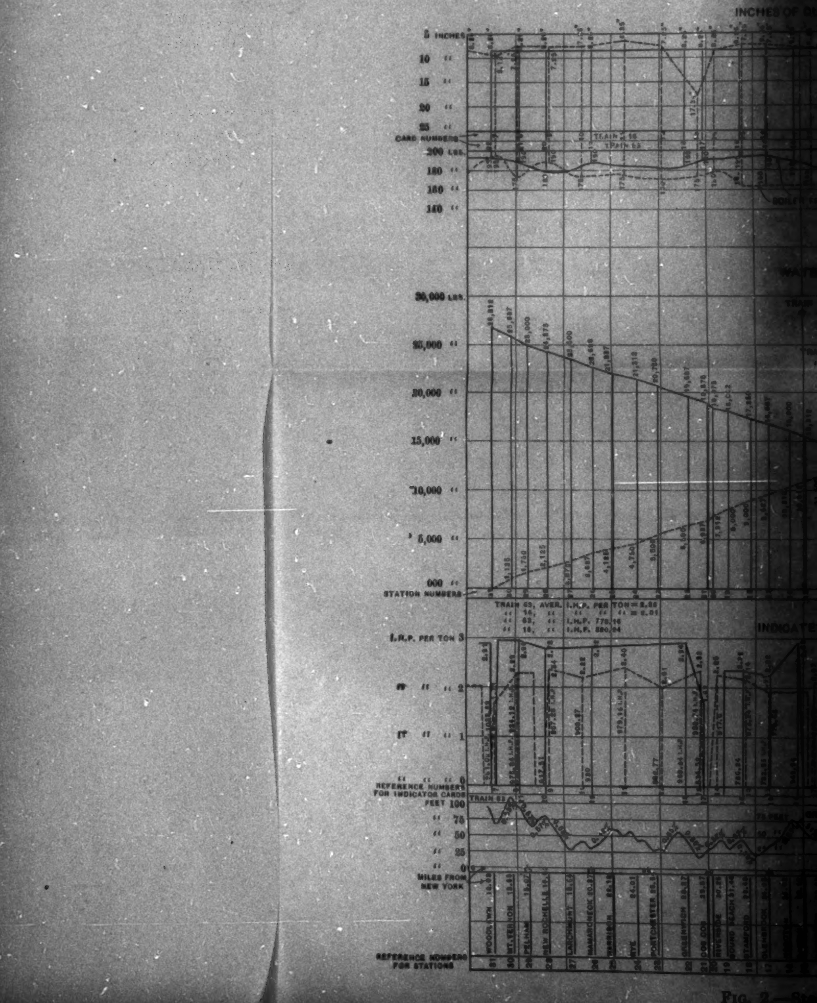


FIG. 2.—St

IVE TESTS

ads.

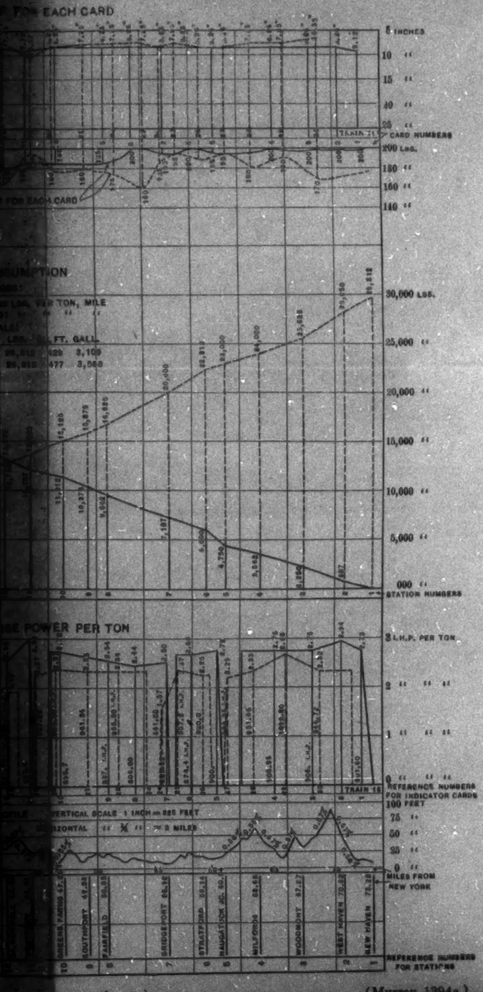
0 lb.

,000 lb.

d tender 232,000 lb.

0 gallons.

Train 16, Sept. 26, 1905.
Shown by dotted lines.
Weight of train with engines 403,08 tons.
5 cars in train.
Schedule time—1 hour, 15 min.
Actual time—1 hour, 17 min., 30 sec.



xpress runs (pass.)

(Murray 1394a.)

Train 63, Sept. 22, 1905.
Shown by full lines.
Weight of train with engine—325.88 tons.
5 cars in train.
Schedule time—1 hour, 12 min.
Actual time—1 hour, 16 min., 40 sec.

Engi
Size o
Size
Worki
Weigh
Weigh
Tank

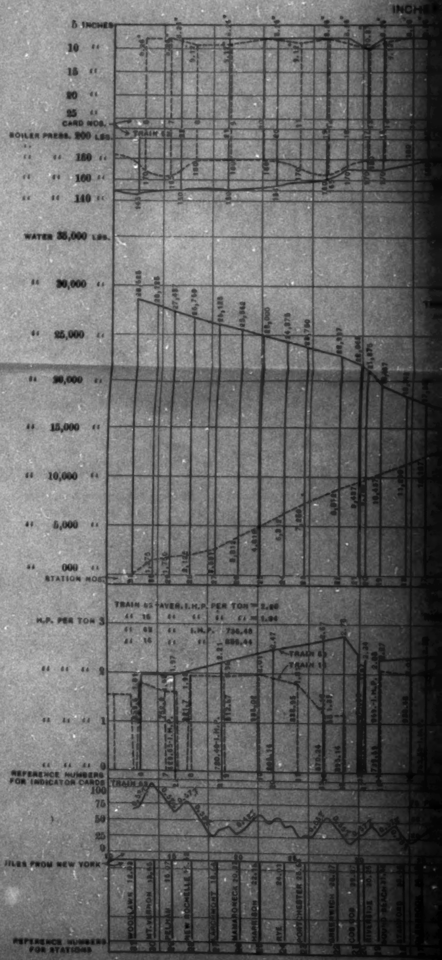
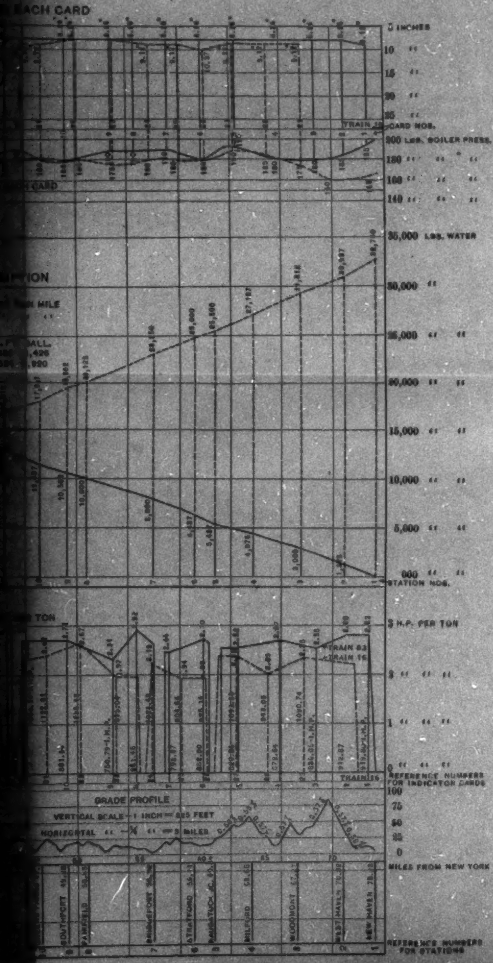


FIG. 3.

TESTS

lb.
der 232,000 lb.
es.

Train 16, Sept. 16, 1905.
Shown by dotted lines.
Weight of train with engine 465.46 tons.
6 cars in train.
Schedule time, 1 hour, 15 min.
Actual time—1 hour, 16 min., 40 sec.

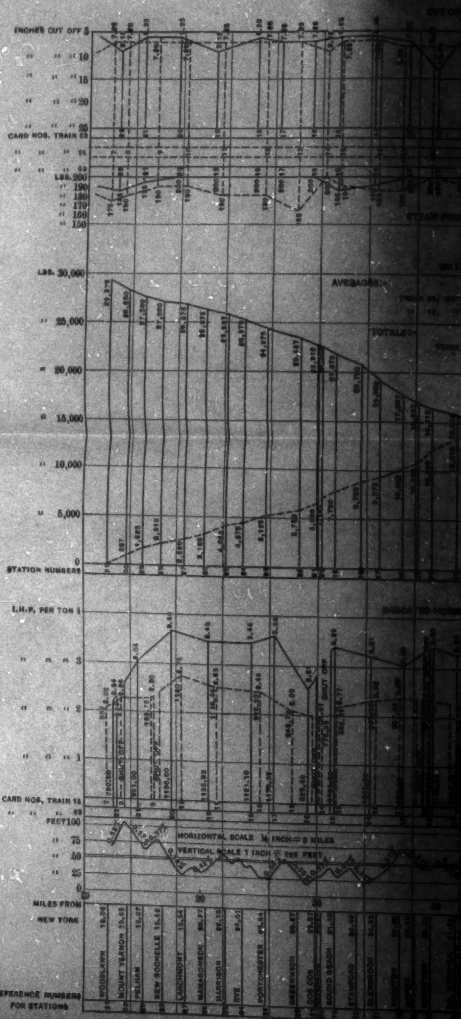


ns (pass.)

(Murray 1394b.)

Train 63, Sept. 27, 1906.
Shown by full lines.
Weight of train with engine, 325.86 tons.
5 cars in train.
Schedule time 1 hour, 12 min.
Actual time 1 hour, 11 min.

Engine 1310.
Size cylinder
Size wheel 78".
Working pressure
Weight on drivers
Weight of engine
Type, American.
Tank capacity



TIVE TESTS

ynopsis.

x28°.

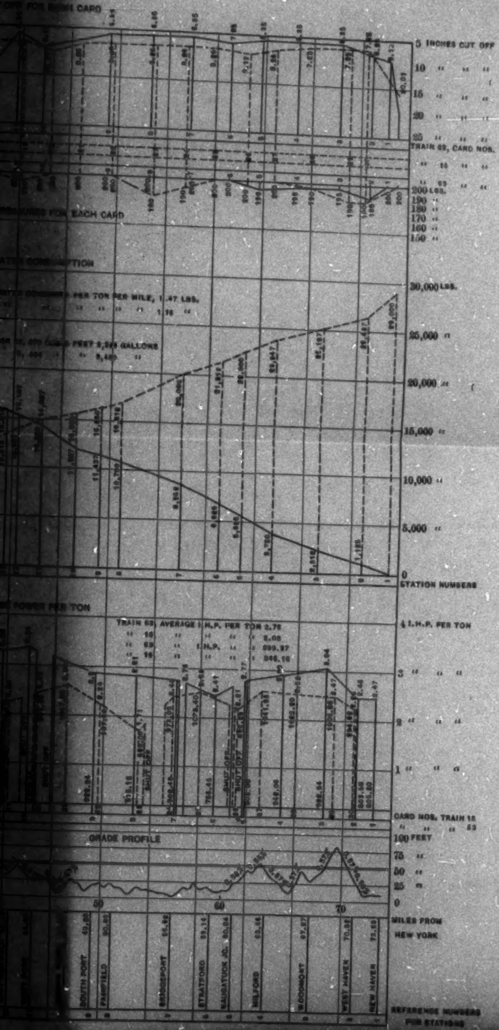
e 200 lb.

s 88,000 lb.

and tender 232,000 lb.

600 gallons.

Train 16, Sept. 27, 1905.
Shown by dotted lines.
Weight of train with engine, 406.33 tons.
5 cars in train.
Schedule time 1 hour, 15 min.
Actual time 1 hour, 14 min. 18 sec.



Train 63, Sept. 28, 1905.
Shown by full lines.
Weight of train with engine—329.3 tons.
5 cars in train.
Schedule time—1 hour, 12 min.
Actual time—1 hour, 10 min., 35 sec.

Engine
Size cyli
Size whe
Working
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Weight
Type, A
Tank ca

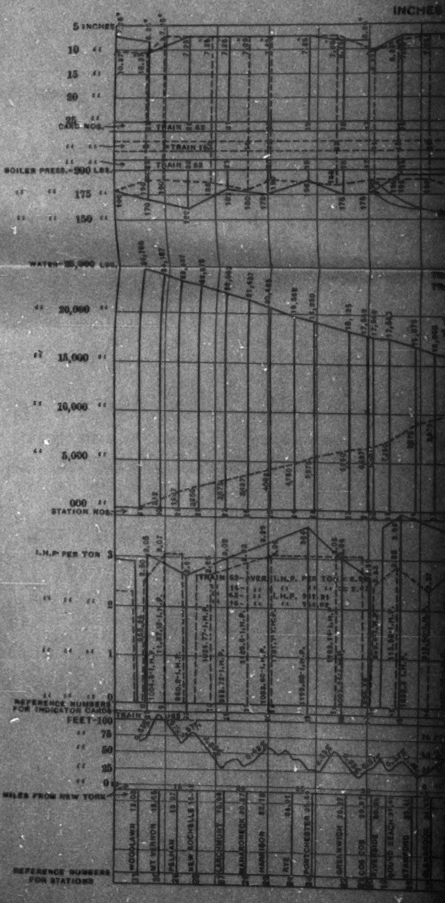
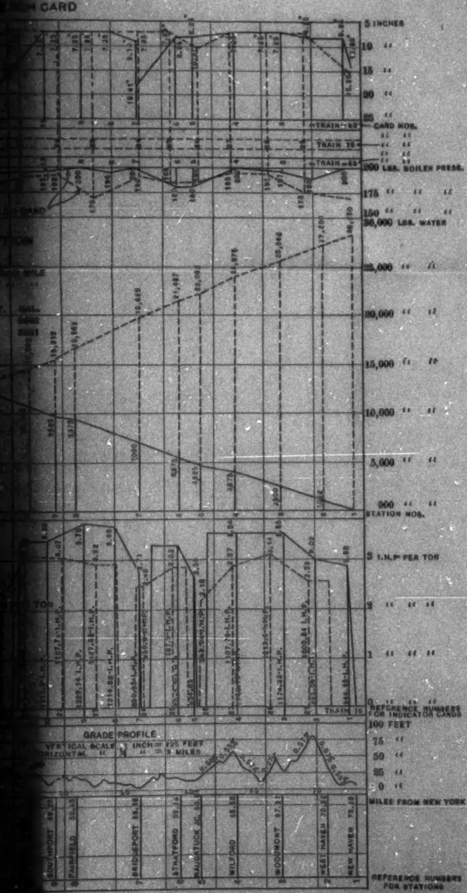


FIG. 5.—S

,000 lb.

Train 16, Sept. 28, 1905.
Shown by dotted lines.
Weight of train with engine—386.57 tons.
5 cars in train.
Schedule time 1 hour, 15 min.
Actual time—1 hour, 11 min., 20 sec.

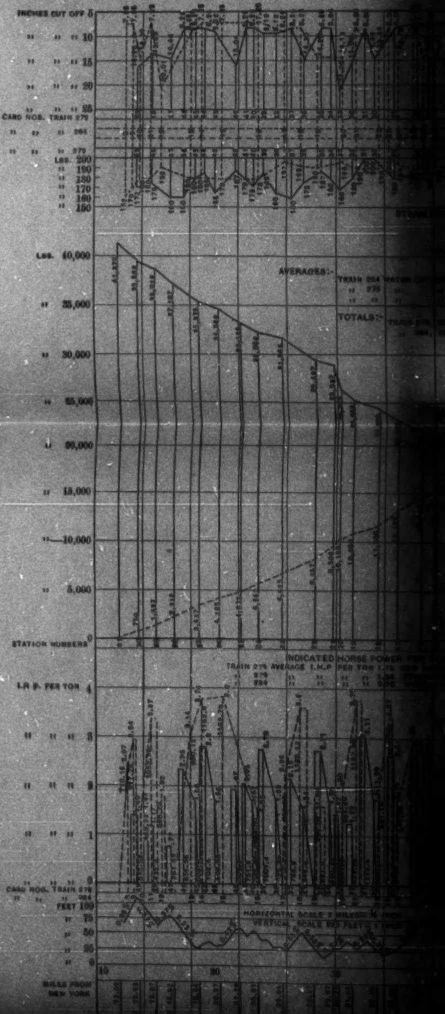


(pass.)

(Murray 1304d)

Train 279, Sept. [illegible], 1906.

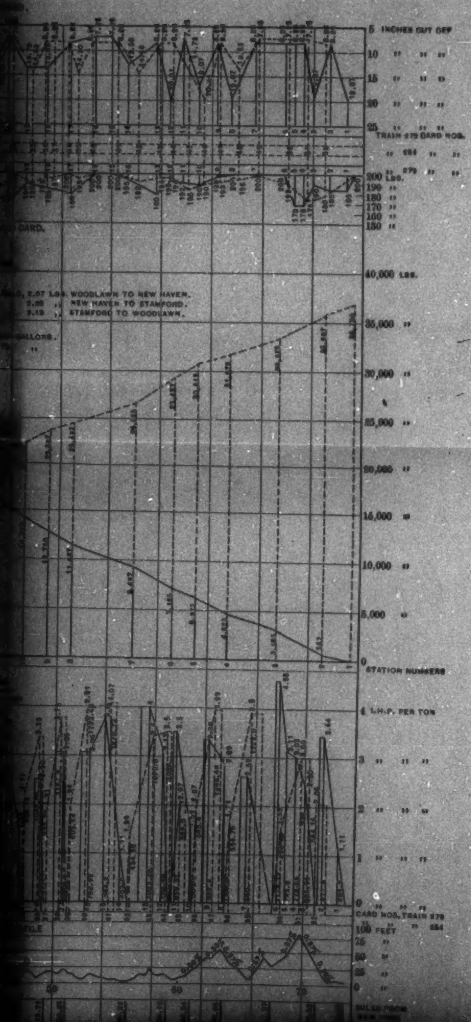
Shown by full lines.
Weight of train with engine, New Haven to Stamford 255.6 tons.
Weight of train with engine, Stamford to Woodlawn, 366.02 tons.
4 cars in train to Stamford, 7 cars to Woodlawn.
Schedule time 2 hours, 32 min., New Haven to Woodlawn.
Actual time 2 hours, 47 min., 40 sec., New Haven to Woodlawn.
Schedule time, New Haven to Stamford, 1 hour, 38 min.
Actual time, New Haven to Stamford, 1 hour, 47 min., 35 sec.
Schedule time Stamford to Woodlawn, 54 min.
Actual time Stamford to Woodlawn, 1 hour, 5 min



lb.
ender 232,000 lb.

llons.

Train 294, Sept. 29, 1908.
Shown by dotted lines.
Weight of train with engine, 312.65 tons.
6 cars in train.
Schedule time, 2 hours, 7 min
Actual time, 2 hours, 7 min.



Shown by full lines.
Weight of train with engine.
252.2 tons, 4 cars, New Haven to Stamford.
364.6 tons, 7 cars, Stamford to Woodlawn.
Schedule time, 2 hours, 32 min., New Haven to Woodlawn.
Actual time, 2 hours, 39 min., 30 sec., New Haven to Woodlawn.
Schedule time, New Haven to Stamford, 1 hour, 38 min.
Actual time, New Haven to Stamford, 1 hour, 44 min., 40 sec.
Schedule time, Stamford to Woodlawn, 54 min.
Actual time, Stamford to Woodlawn, 54 min., 7 sec.

Size
Size
Work
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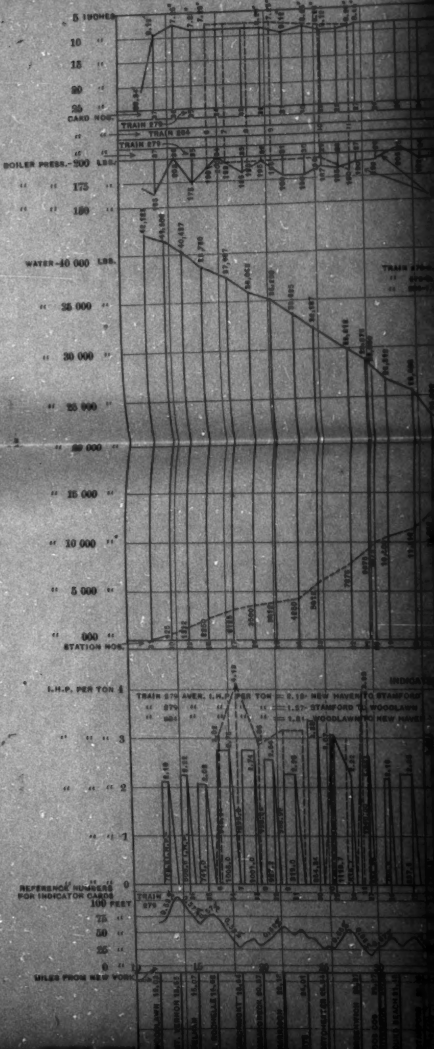
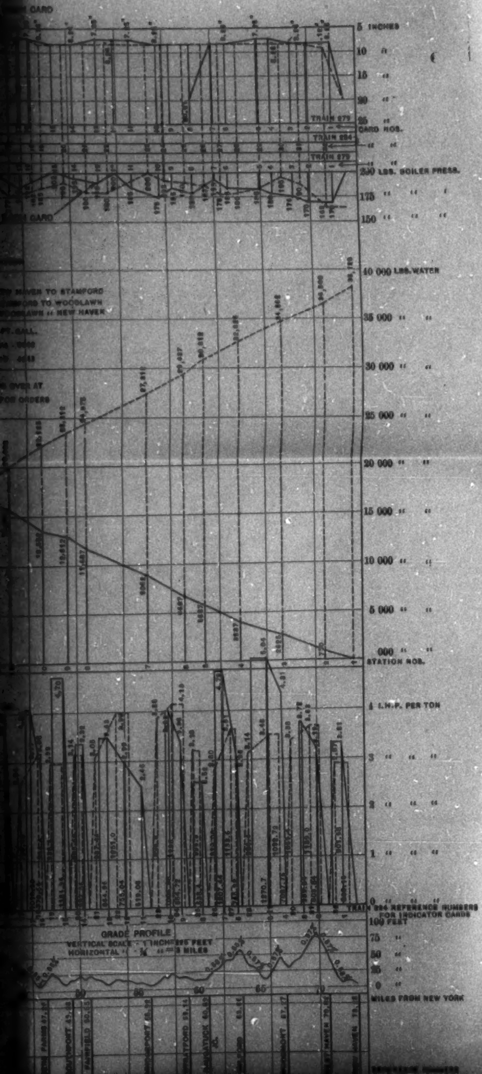
Type
Tank



[illegible] Sept. 25, 1905.
Shown by dotted lines.
Weight of train with engine, 313.8 tons.
6 cars in train.
Schedule time, 2 hours, 7 min.
Actual time, 2 hours, 7 min.

lb.
r, 232,000 lb.

ons.



Train 279, Oct. 2, 1905.

Shown by full lines.

Weight of train with engine, New Haven to Stamford, 262.26 tons.

Weight of train with engine, Stamford to Woodlawn 379.15 tons.

4 cars in train to Stamford, 7 cars to Woodlawn.

Schedule time, 2 hours, 32 min., New Haven to Woodlawn.

Actual time, 2 hours, 46 min., 45 sec., New Haven to Woodlawn.

Schedule time, New Haven to Stamford, 1 hour, 38 min.

Actual time, New Haven to Stamford, 1 hour, 45 min., 30 sec.

Schedule time, Stamford to Woodlawn, 54 min.

Actual time, Stamford to Woodlawn, 1 hour, 15 min.

Engi
Size
Size
Work
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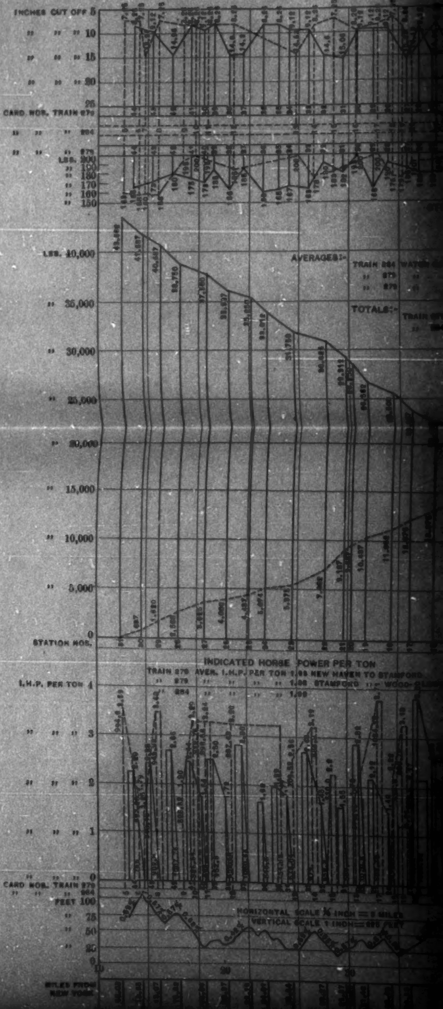
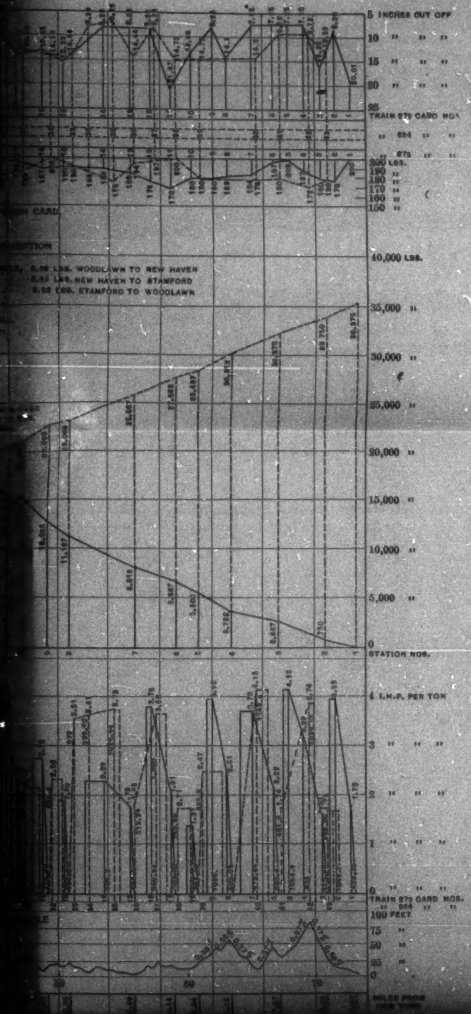
Type
Tank



232,000 lb.

Train 284, Oct. 2, 1906.
Shown by dotted lines.
Weight of train with engine, 276.9 tons.
5 cars in train.
Schedule time 2 hours, 7 min.
Actual time 2 hours, 8 min., 15 sec.



ford 245.67 tons.
Weight of train with engine, Stamford to Woodlawn 316.55 tons.
5 cars in train to Bridgeport, 4 cars to Stamford.
6 cars in train to Woodlawn.
Schedule time 2 hours 32 min., New Haven to Woodlawn.

Schedule
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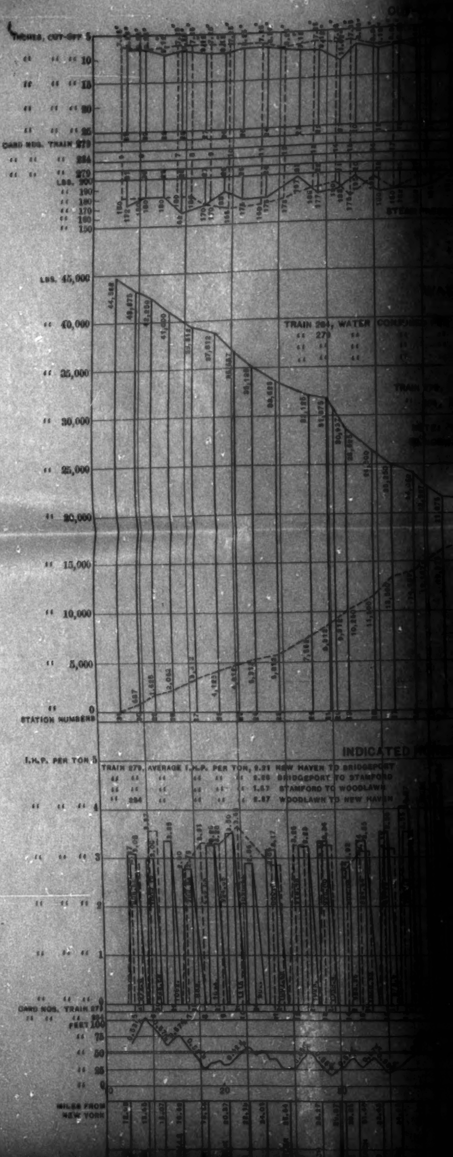


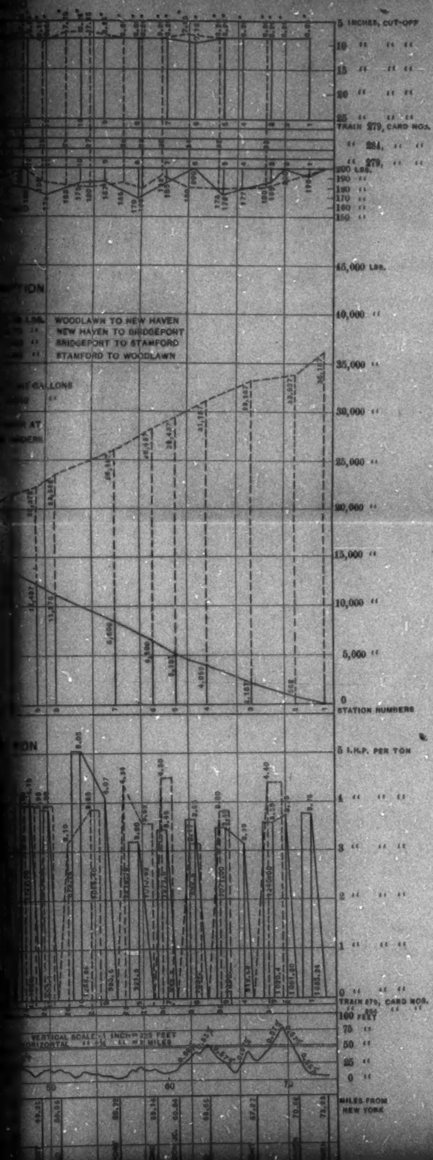
Bridgeport to

c., Bridgeport

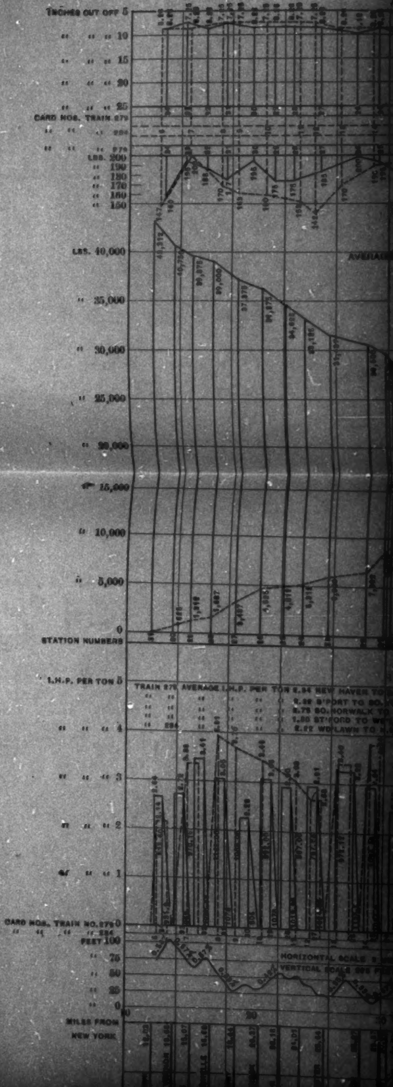
to Woodlawn.
nford to Wood-

Synopsis.

Engine 1210.
Size cylinder 20″x26″.
Size wheel 78″.
Working pressure 200 lb.
Weight on drivers 88,000 lb.
Weight of engine and tender 232,000 lb.
Type, American.
Tank capacity, 5,500 gallons.



Bridgeport, 2[illegible].81 tons.
Weight of train with engine, Bridgeport to So. Norwalk, 270.52 tons.
Weight of train with engine, So. Norwalk to Stamford, 247.02 tons.
Weight of train with engine, Stamford to Woodlawn, 350.33. tons.
5 cars in train to So. Norwalk, 4 cars to Stamford.
7 cars in train to Woodlawn.
Schedule time 2 hours, 32 min., New Haven to Woodlawn.



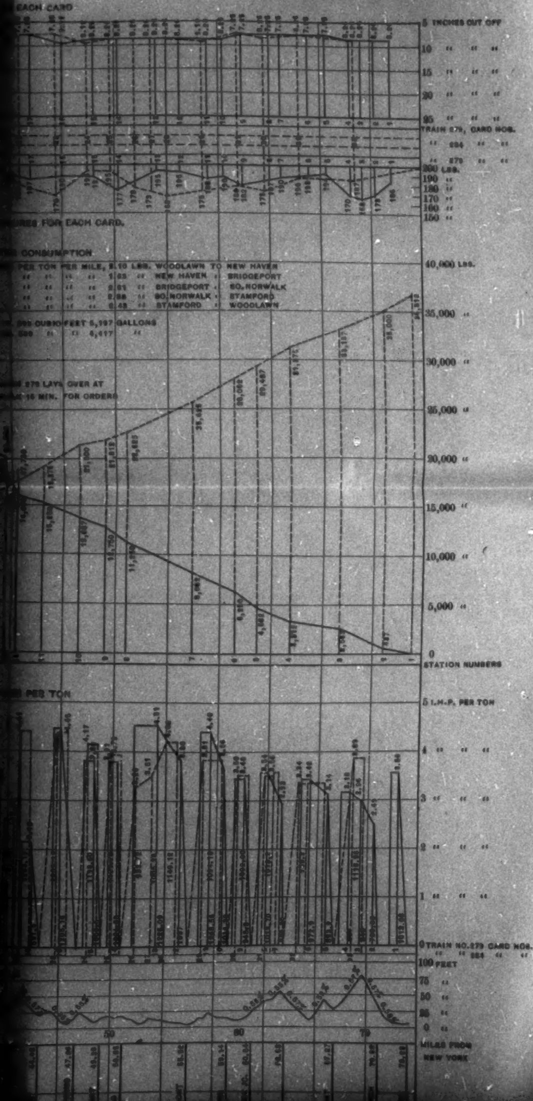
. New Haven to B'port.
B'port. to So. Norwalk.
ort to So. Norwalk.
o Norwalk to Stamford.
sec., So. Norwalk to

Stamford to Woodlawn.
ec., Stamford to Wood-

Schedule time 2 hours, 7 min.
Actual time, 2 hours, 7 min.

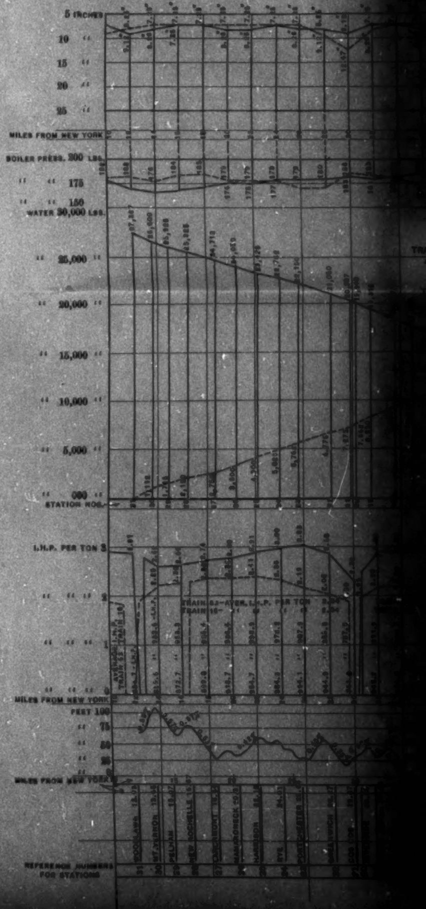
Synopsis.

Engine 1210.
Size cylinder 20"x26".
Size wheel 78".
Working pressure 200 lb.
Weight on drivers 88,000 lb.
Weight of engine and tender 232,000 lb.
Type, American.
Tank capacity 5,500 gallons.



Train 63—Average.

Shown by full lines.
Average weight of train with engine, 328.1 tons.
Average No. of cars, 5.
Schedule time, 1 hour, 12 minutes.
Average time, 1 hour, 13 min., 17 sec.



Tests

xpress Runs

ons.

0 lb.

,000 lb.

tender, 232,000 lb.

gallons.

Train 16—Average.

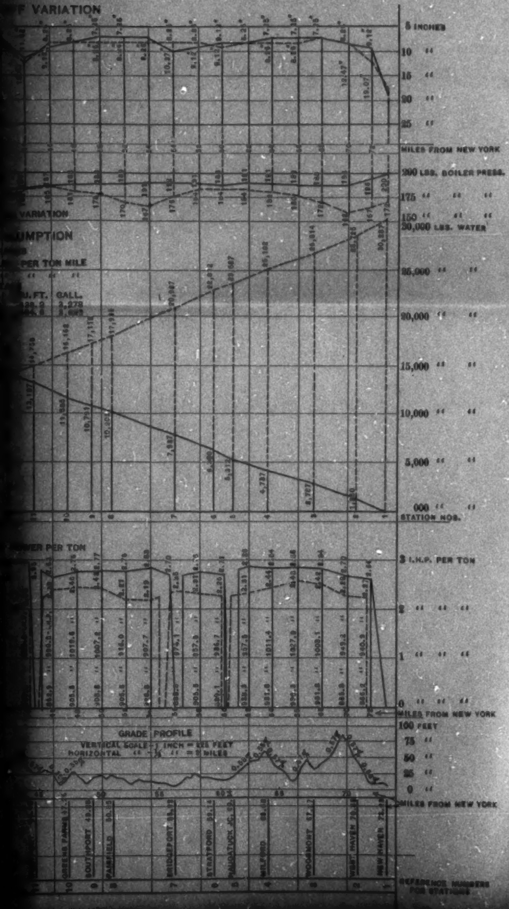
Shown by dotted lines.

Average weight of train with engine, 414.5 tons

Average number of cars, 5.2.

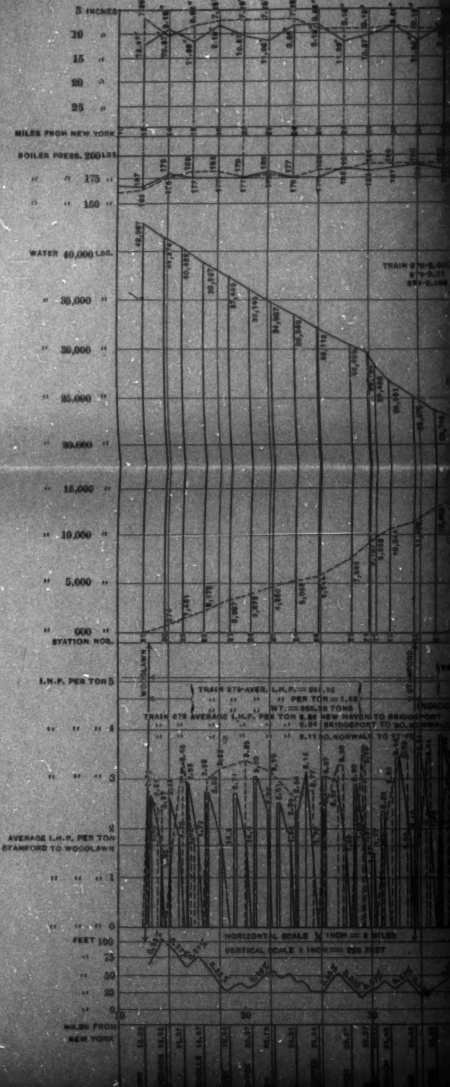
Schedule time, 1 hour, 15 minutes.

Average time, 1 hour, 15 min., 5 sec.



[illegible]
Weight of train with engine [illegible]
[illegible]
355.33 tons 6.8 cars, Stamford to Woodlawn.
Schedule time, 2 hours, 32 min., New Haven to Woodlawn.
Average time, 2 hours, 42 min., New Haven to Woodlawn.
Schedule time, 34 min., New Haven to B'port.
Actual time, 36 min., 39 sec., New Haven to Bridgeport.

Actual time
Stamfor
Schedule tim
Actual time,
lawn.
Average wt.
Average wt.
Average wt.



o. Norwalk to

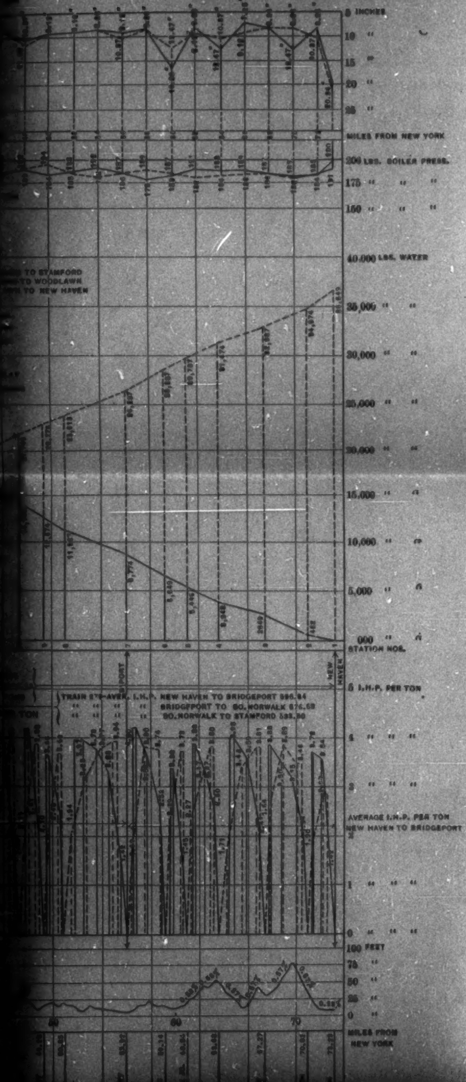
to Woodlawn.
ford to Wood-

t, 268.85 tons.
k, 257.45 tons.
rd, 252.75 tons

shown by dotted lines.
Average weight of train, with engine, [illegible] tons.
Average number of cars, 5.4.
Schedule time, 2 hours, 7 min.
Average time, 2 hours, 7 min., 45 sec.

Synopsis.

Engine 1210.
Size cylinder 20″x26″.
Size wheel 78″.
Working pressure 200 lb.
Weight on drivers 88,000 lb.
Weight of engine and tender, 232,000 lb.
Type, American.
Tank capacity, 5,500 gallons.



express and local schedule between New Haven and New York. The horse power per ton of train movement immediately afforded a check on the capacity of the engine required, showing the normal size of unit to be elected, which, under an arrangement of multiple unit control, permitted the proper amount of engine power to apply to trains of varying weight; the other data most interesting and important to the writer was the water consumption, giving a close check on the relative energy requirements between express and local service. This analysis of the steam engine under operation for trunk line conditions incident to the New Haven Road, caused us to choose for our passenger unit a locomotive, the normal capacity of which was 1000 h.p. at the rim of the locomotive wheels, and this size in practice has borne out our estimate of the capacity required. It may, therefore, be said that for trunk line conditions of the character that obtain on the New Haven Road, a locomotive unit capable of multiple unit operation and of 1000 h.p. continuous capacity, is the proper selection of unit size.

THE STEAM FREIGHT LOCOMOTIVE

Studying the freight engine requirements of a trunk line, from a steam locomotive point of view, I had conducted a series of tests on typical freight (or road) engines, the runs being over a distance of 55½ miles, and in this case trains in the regular log of the New Haven operation, varying in weights between 720 and 1500 tons, including weight of engine, were used.

Figs. 13, 14, 15 and 16 show east and west operation of trains in the vicinity of 1000 tons, and typify the average runs of trains; these figures show cut-off, boiler pressure, speed and miles per hour, indicated horse power—besides giving other data with reference to the class of engine, size of cylinders, weights, etc.

Table 1 shows the summation of ten tests, giving grand averages for the ten runs.

It is interesting to note in these figures that the average evaporation of water per pound of coal is 6.9; also to note in the runs indicated on Fig. 13 to 16, inclusive, that the average indicated horse power varies from 655 minimum to 892 maximum; the average speed varying from 23.5 miles per hour minimum to 31.5 miles per hour maximum.

The electrical locomotive we have designed to handle our general class of freight service, or what could be correctly called our electric freight road engine, has a normal horse power rating of

FREIGHT LOCOMOTIVE TESTS

Midway to New Haven and return

Train—O-B-2.
Date, 7-5-10.
Number of loaded cars 40—40 cars N. H. to Saybrook.
Total number of cars, 40 (39 cars Saybrook to N. L.; 38 cars N. L. to Midway.)
Weight of train, including engine, tender and caboose, (1468 N. H. to Saybrook; 1424 Saybrook to N. L.; 1400 N. L. to Midway).

Engine 457 Mogul type.
Cylinders 20″x28″—63″ drivers.
Boiler pressure, 200 lb.
Weight on drivers 131600 lb.
Weight of engine, tender and caboose, 140 tons.

Train—M-O-1.
Date, 7-1-10.
Number of loaded, cars 8.
Total number of cars, 51.
Weight of train, including engine, tender and caboose, 1091 tons.

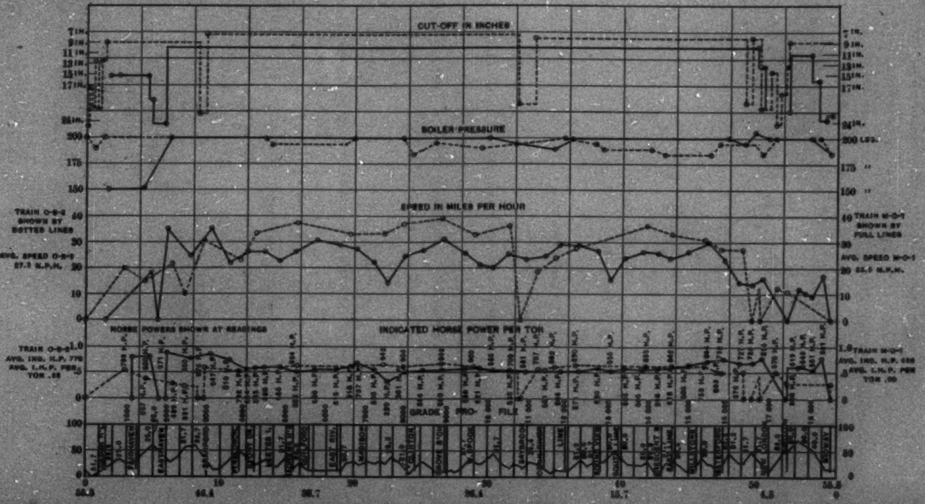


Fig. 13.—Steam freight runs

Freight Locomotive Tests

Midway to New Haven and return

Train—O-B-2.
Date, 7-7-10.
Number of loaded cars 36 (36 New Haven to New London.
Total number of cars 36 (35 New London to Midway).
Weight of train, including engine, tender and caboose, (1357 N. H. to N. London; 1333 N. L. to Midway).

Engine 457. Mogul type.
Cylinders 20″x28″. 63″ drivers.
Boiler pressure, 200 lb.
Weight on drivers, 131,600 lb.
Weight of engine, tender and caboose, 140 tons.

Train—M-O-1.
Date, 7-7-10.
Number of loaded cars, 8.
Total number of cars, 46.
Weight of train including engine, tender and caboose, 1105 tons.

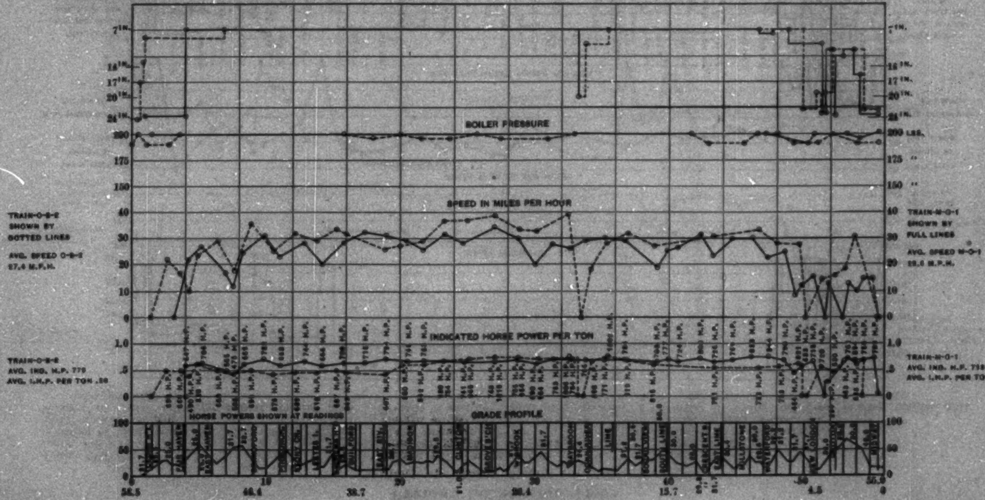


FIG. 14.—Steam freight runs

FREIGHT LOCOMOTIVE TESTS

Midway to New Haven and return

Train, O-B-2.
Date, 7-8-10.
Number of loaded cars, 41.
Total number of cars, 41.
Weight of train including engine, tender and caboose, 1526 tons.

Engine 457, Mogul type.
Cylinders 20″x28″, 63″ drivers.
Boiler pressure, 200 lb.
Weight on drivers, 131,600 lb.
Weight of engine, tender and caboose, 140 tons.

Train, M-O-1.
Date, 7-8-10.
Number of loaded cars, 8.
Total number of cars, 45.
Weight of train including engine, tender and caboose, 991 tons.

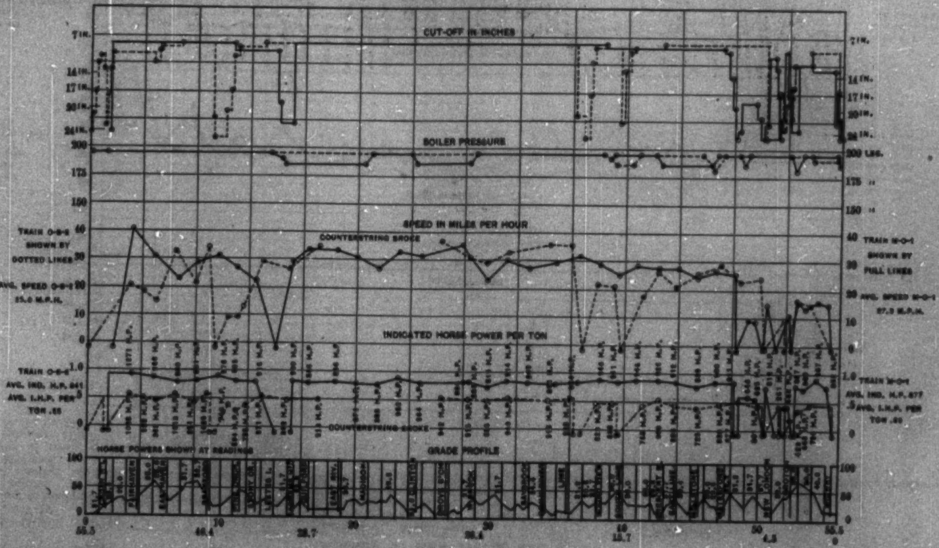


Fig. 15.—Steam freight runs

FREIGHT LOCOMOTIVE TESTS
Midway to New Haven and return

Train, O-B-2.
Date, 7-9-10.
Number of loaded cars, 37.
Total number of cars, 37.
Weight of train, including engine, tender and caboose, 1314 tons.

Engine 457, Mogul type.
Cylinders 20"x28". 63" drivers.
Boiler pressure, 200 lb.
Weight on drivers, 131,600 lb.
Weight of engine, tender, and caboose, 140 tons.

Train, M-O-1.
Date, 7-9-10.
Number of loaded cars, 13 N. H., 14 N. L.
Total number of cars, 37 N. H., 38 N. L.
Weight of train including engine, tender and caboose, 966 m.-N. L., 922 N. L.-N. H.

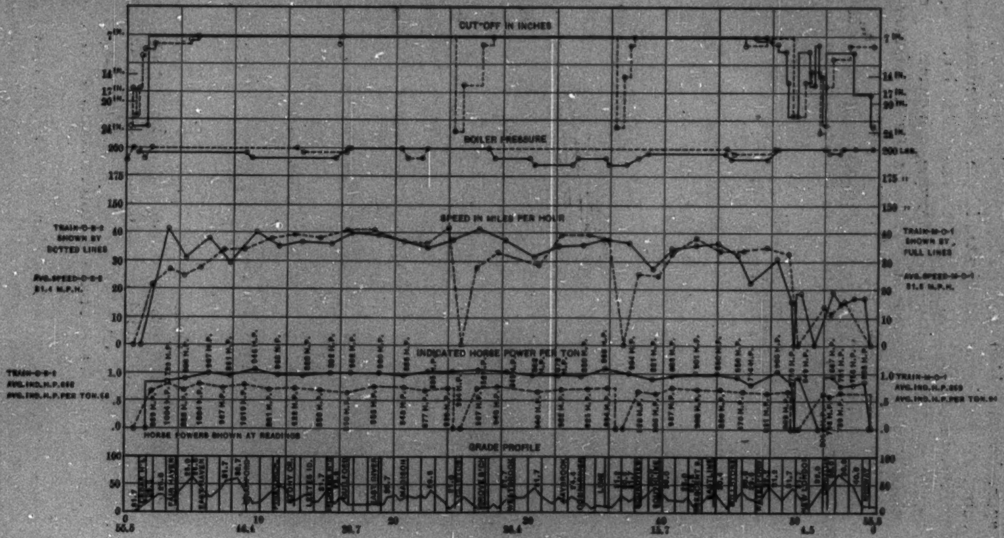
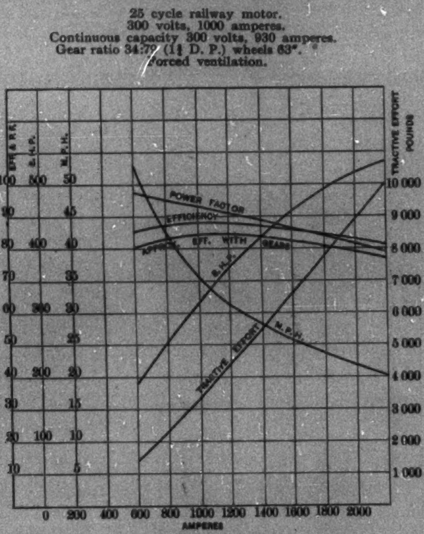


FIG. 16.—Steam freight runs

approximately 1400 h.p. This capacity provides a margin above the requirements indicated in the recorded tests as shown in Figs. 13, 14, 15 and 16. The excess capacity, however, is highly desirable in virtue of it affording the electric locomotive an opportunity to operate heavier trains and at a higher schedule speed than the steam locomotive it replaces.

Fig. 17 shows the motor characteristics of our electric road freight engine 071, and Fig. 18 is a record of tests made on locomotive 071 operating on N. Y. N. H. & H. rails between Stamford and New Rochelle, hauling a dead steam locomotive with thirty-seven freight cars and caboose—the total weight of train being 1438 tons. It is to be noted that data on this test is inclusive of voltage applied to motors, amperes, total kilowatts and speed.



25 cycle railway motor.
300 volts, 1000 amperes.
Continuous capacity 300 volts, 930 amperes.
Gear ratio 34:79 (1¾ D. P.) wheels 63".
Forced ventilation.

FIG. 17.—Speed torque characteristics of one of the motors of Locomotive No. "071"

It is of interest to note that the average speed over a distance of 1675 miles was 36.5 miles an hour; the average kilowatt input

LOCOMOT

Test No.	1 C		2 C		3 C		4 C	
Date	5-18-10		5-19-10		5-20-10		5-23-10	
Engine No.	457		457		457		457	
Train No.	M-O-1	O-B-2	M-O-1	O-B-2	M-O-1	O-B-2	M-O-1	O-B-
Distance—miles	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5
No. of cars loaded	5/6	43	1	40	5	43	5	44
No. of cars total, incl. caboose	44/45	44	40	41	60	44	29	45
Wgt. of train, incl. eng. and tender	968/1001	1496	860	1391	1219	1493	720	1540
Ton-miles total	55400	83040	47730	77210	67660	82870	39960	85480
Lb. of coal per 1000 ton miles	96.8		99.8		93.0		88.7	
Lb. of water per 1000 ton miles	807	498	876	555	682	520	853	481
No. of stops	7	4	2	8	5	3	7	3
Schedule running time	3h-10m	2h-45m	3h-10m	2h-45m	3h-10m	2h-45m	3h-10m	2h-45
Actual running time	2h-35m	2h-12m	2h-14m	2h-30m	2h-38m	2h-18m	1h-57m	2h-27
Actual time standing	0h- 7m	0h-33m	0	0h-18m	0h- 4m	0h- 9m	0h-24m	0h- 4
Total time on road	2h-42m	2h-45m	2h-14m	2h-48m	2h-42m	2h-27m	2h-21m	2h-31
Avg. speed running miles per hr.	21.5	25.3	24.9	22.2	21.1	22.5	28.6	22.7
Avg. boiler pressure	200	200	200	200	200	200	200	200
Time throttle open	2h-30m	2h- 2m	2h- 6m	2h-10m	2h-15m	1h-57m	1h-36m	2h-14
Total water used	44690	41370	41820	42880	46130	43070	34080	41070
Avg. water rate, lb. per hour	17880	20350	19910	19790	20500	22070	21300	18250
Coal burned running	13,400		12,475		14,000		11,130	
Apparent evaporation, lb.	6.42		6.79		6.37		6.75	

Tests made, Midway to New Haven and return.
Weight of engine tender and caboose = 140 tons.
Note: When two different numbers of cars are shown it means that the first number was carried from Midw and the second number from New London to New Haven

GHT SERVICE

6 C		7 C		8 C		9 C		10 C		Average	
525-10		5-26-10		5-27-10		5-31-10		6-1-10			
457		457		457		457		457		457	
M-O-1	O-B-2	M-O-1	O-B-2	M-O-1	O-B-2	M-O-1	O-B-2	M-O-1	O-B-2	M-O-1	O-B-2
55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5
13/12	44	1	41	4	42	0	34	1	41	4.4	41.7
50/49	45	58	42	48	43	21	35	42	43	44	43
1065/1066	1500	1119	1500	992	1490	505	1315	894	1463	948	1471
58690	83260	62110	83260	55050	82700	28030	72990	49620	81200	52610	81665
87.3		86.9		94.0		93.5		92.9		92.2	
784	524	726	506	810	562	1047	575	872	552	816.7	528.7
7	4	5	5	4	6	4	5	2	9	4.9	4.9
3h-10m	2h-45m	3h-10m	2h-45m	3h-10m	2h-45m	3h-10m	2h-45m	3h-10m	2h-45m	3h-10m	2h-45m
2h-37m	2h-20m	2h-41m	2h-25m	2h-22m	3h-11m	1h-47m	2h-42m	2h-15m	2h-26m	2h-20m	2h-29m
0h-21m	0h-28m	0h-10m	0h-19m	0h- 7m	0h-25m	0h-23m	0h-29m	0h-12m	0h-36m	11.6m	22.7m
2h-58m	2h-48m	2h-51m	2h-44m	2h-29m	3h-36m	2h-10m	3h-11m	2h-27m	3h- 2m	2h-32m	2h-52m
21.2	23.8	20.8	23.0	23.4	17.5	31.2	20.6	24.7	22.8	23.7	22.5
200	200	200	200	200	200	200	200	200	200	200	200
h-12m	2h- 7m	2h-30m	2h- 1m	2h-10m	2h-24m	1h-37m	2h-16m	2h- 6m	2h- 8m	2h- 7m	2h- 8m
46000	43630	45070	42130	44570	46505	29340	41950	43260	44820	41890	43100
20910	20780	18030	20890	20570	19380	18180	18500	20600	21000	19818	20208
12,400		12,630		12,950		9,450		12,150		12,370	
7.23		6.90		7.03		7.54		7.25		6.90	

(Murray 1400.)

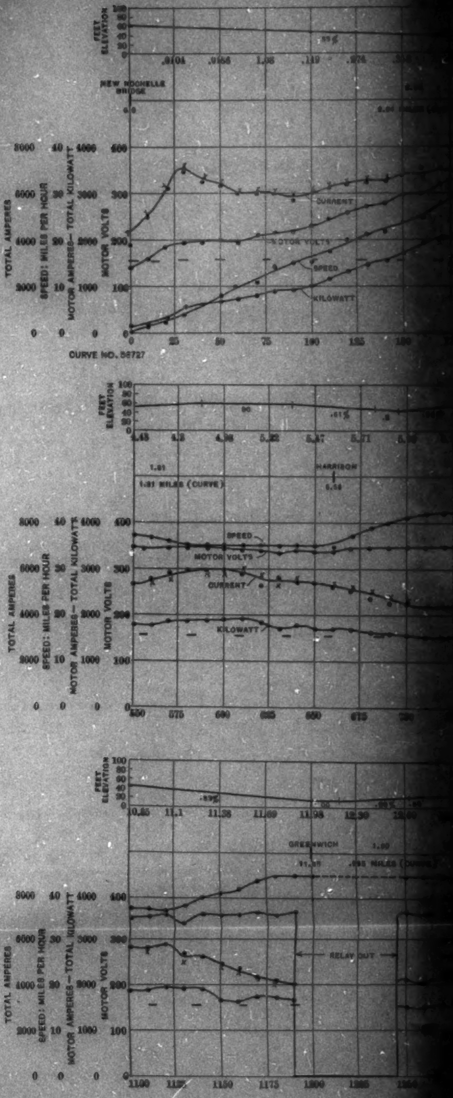
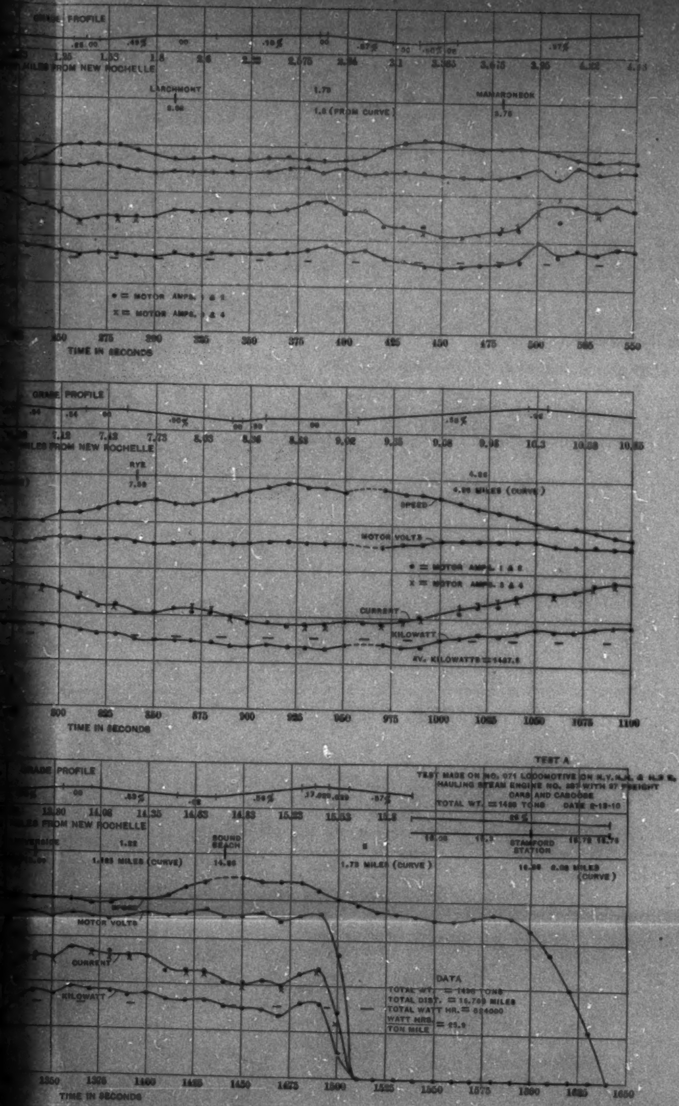

FEET ELEVATION
.0104
.0166
1.08
.119
.274
NEW ROCHELLE BRIDGE
TOTAL AMPERES
SPEED: MILES PER HOUR
MOTOR AMPERES—TOTAL KILOWATT
MOTOR VOLTS
CURRENT
MOTOR VOLTS
SPEED
KILOWATT
CURVE NO. 56727
0
25
50
75
100
125
150
FEET ELEVATION
4.2
4.96
5.22
5.47
5.71
1.81
1.81 MILES (CURVE)
HARRISON
SPEED
MOTOR VOLTS
CURRENT
KILOWATT
550
575
600
625
650
675
FEET ELEVATION
10.85
11.1
11.36
11.69
11.98
12.30
GREENWICH
RELAY OUT
1100
1125
1150
1175
1200
1225
1250

FIG. 18.



71" hauling 1438 tons freight

(Murray 1400a.)

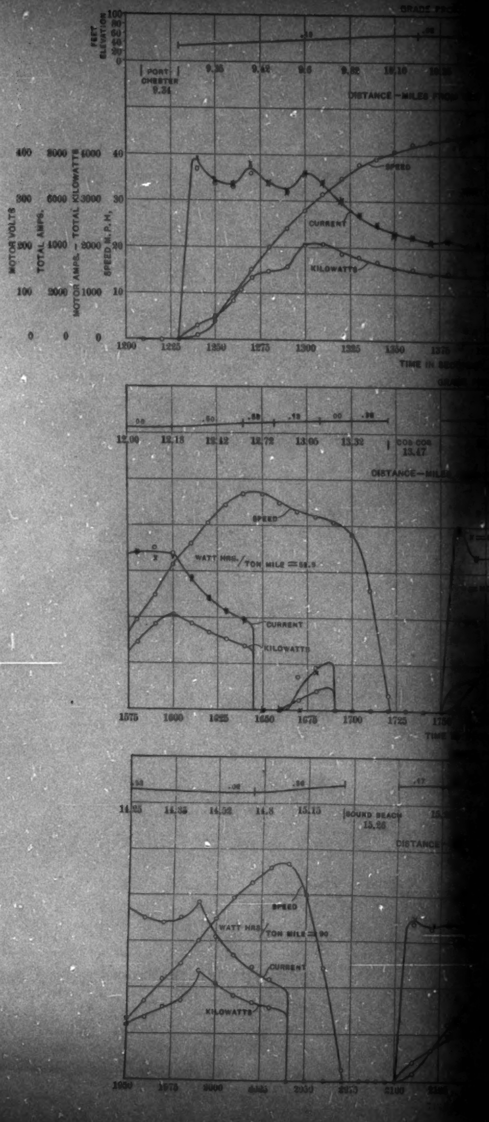
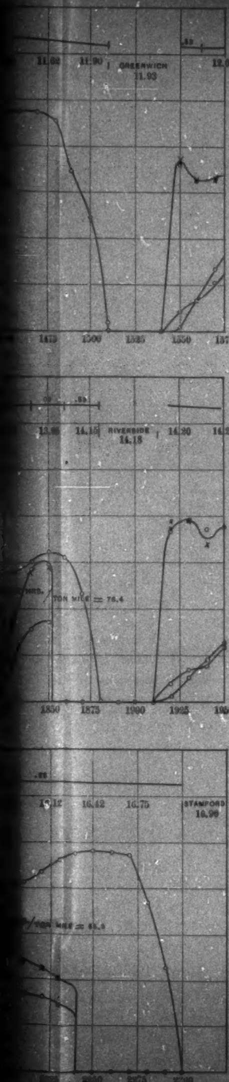

GRADE PRO
FEET ELEVATION
100
80
60
40
20
0
.19
.02
PORT CHESTER 9.34
9.36
9.42
9.6
9.82
10.10
DISTANCE—MILES FROM
MOTOR VOLTS
TOTAL AMPS.
MOTOR AMPS.—TOTAL KILOWATTS
SPEED M.P.H.
400
300
200
100
0
8000
6000
4000
2000
4000
3000
2000
1000
40
30
20
10
SPEED
CURRENT
KILOWATTS
1200
1225
1250
1275
1300
1325
1350
1375
TIME IN SECONDS
GRADE
.00
.50
.33
.13
.00
.33
12.00
12.18
12.42
12.72
13.05
13.32
COS COB 13.47
DISTANCE—MILES
SPEED
WATT HRS./TON MILE = 52.5
CURRENT
KILOWATTS
1575
1600
1625
1650
1675
1700
1725
1750
TIME
.33
.36
.36
.17
14.25
14.35
14.52
14.8
15.15
SOUND BEACH 15.26
DISTANCE
SPEED
WATT HRS./TON MILE = 90
CURRENT
KILOWATTS
1950
1975
2000
2025
2050
2075
2100

FIG. 10.—Locom



DATA

TOTAL WT. = 500 TONS
TOTAL DIST. = 16.9 MILES
TOTAL WATT HRS. = 496.700
WATT HRS./TON MILE = 58.8
COMPRESSOR RUNNING 10' 12''
OR 26.6 % OF TOTAL TIME

TEST B

TEST MADE ON NO. 071 LOCOMOTIVE ON N.Y.N.H. & H. R.R.
HAULING 500 TON PASSENGER TRAIN IN LOCAL
SERVICE BETWEEN NEW ROCHELLE
AND STAMFORD, CONN.

TOTAL WT. = 500 TONS DATE 5-12-13

CURVE NO. 56728

g 500 tons pass.

(Murray 1400b)

being 1,487 kw. with an average rim horse power at the drivers of 1650 h.p., and notwithstanding the locomotive was dragging a dead engine throughout this run, it accomplished the work at an average energy rate of 25.9 watt-hours per ton-mile.

Not uninteresting is the flexibility offered by the electric over a steam locomotive, in noting that its limitation of service is not absolutely confined to one class. Fig. 19 is a record of the same locomotive (071) making a local schedule in passenger service handling a total train weight of 500 tons; and notwithstanding the high ratio of the time of acceleration to total time of schedule, it is to be noted that the watt-hours per ton-mile were under 60.

Test No. 1-A
Harlem River Yard, April 8, 1910.
Water used, 38,600 lb.
Anthracite coal used, 5540 lb.
Apparent evaporation, 6.98 lb.

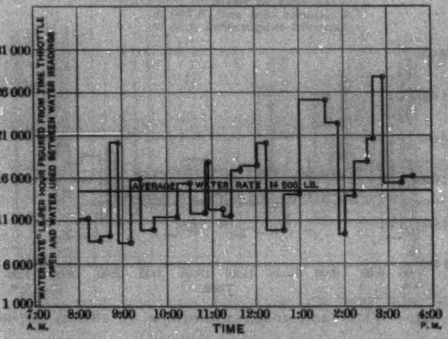


FIG. 20.—Water and coal consumption on switch engine

THE STEAM LOCOMOTIVE SWITCHER

By far the most interesting investigation of the four types of steam engines employed in trunk line service was that of the steam switching locomotive, and a careful insight into its daily work revealed characteristics most surprising to the writer. In the many yards of the New Haven lines none afforded a better opportunity to study this type of engine than at Harlem River, where the duty imposed upon the switching locomotive, beside that of classification, included also float work, calling into account the necessity of heavy drafts of power and sustained for periods longer than usual to other switching yards; but even with this additional duty to perform, the relatively small amount of energy required for this work yielded, as before stated, a great surprise. From April 8th to April 29th, 1910 inclusive, careful observations for twelve days of switching movements were made on our switch engine 2,392; nine days of which were in the Harlem River yard and three in the Oak Point yard. The log sheets of tests include reading of water meters taken at frequent intervals, average boiler pressure, time throttle open, time engine in motion or standing, total cars handled, notation of loads and empties. Space permitting, complete detail data sheets of the twelve days' record would be included. I have taken, however, four of these data sheets with their respective curves plotted for water consumption, and again it is to be noted how very closely the data sheets and curves check one another. Careful measurements of coal weights were made, in order to secure the resulting rate of evaporation which is given, and is noted to approximate seven pounds of water per pound of coal.

Test No. 4-A
Harlem River Yard, April 13, 1910.
Water used, 37,200 lb.
Anthracite coal used, 5,700 lb.
Apparent evaporation, 6.53 lb.

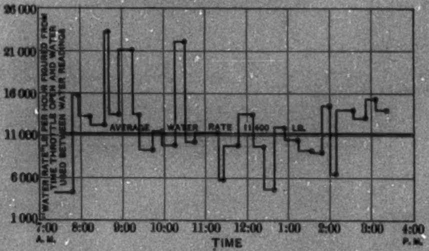


FIG. 21.—Water and coal consumption on switch engine

As an interesting record of the practical method of coaling a switching locomotive for an eight-hour shift, herewith are quoted the words of the engineer in his report with reference to these tests:

"About a half hour before going to work each morning the tank was loaded with 8000 lb. of hard coal. The engine was then taken to the pit and fire cleaned, and a new fire of coal built in her. To build this first fire required about 2,500 lb. of coal, and the engine worked on it for about three hours. At the end of three hours the grates were shaken and the fire dressed and built up with about 1500 lb. more coal. This second fire lasted about two hours, and at the end of that time the grates were again shaken, fire dressed and the third and last fire built. This required about 1500 lb. and lasted until the finish of the eight hours' work.

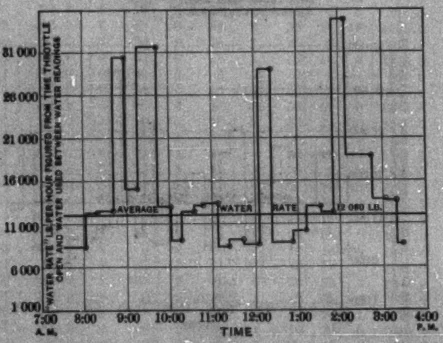

Test No. 8-A
Harlem River Yard, April 21, 1910.
Water used, 38,700 lb.
Anthracite coal used, 5,450 lb.
Apparent evaporation, 7.10 lb.

FIG. 22—Water and coal consumption on switch engine

"After the day's work was completed the engine was taken to the house with coal remaining on her, and enough coal left in the tank to keep the fire until the next morning when the engine went to the pit to have fire cleaned and built up for the day's work".

It would be to go ahead of our story to speak of an electric switcher here, but does not the above described operation suggest it?

Again, space does not offer the opportunity to discuss the hourly movement of the engine in the yard. One brief paragraph from the testing engineer's report will suffice:

"When not pulling and loading floats the engine was employed making up trains to load floats, and doing other miscellaneous work".

Not uninteresting, too, is the closing paragraph of his report, which quoted is as follows:

"On following the work of engines, one is forced to the conclusion that the ratio of weight to tractive effort is too low. This may be due to poor trackage, road-bed, etc., but even with sanded rails and all other conditions available the engines are inclined to slip, thus losing time in accelerating. This is a bad fault in a switching locomotive, and especially bad in such yards as Harlem River and Oak Point, for since the speed is limited and the coupling, uncoupling, connecting air, etc., can be only done so rapidly, the only method of increasing the amount of work done is to increase the accelerating power of the engine used". There is, of course, this much to be taken into consideration—that the more constant torque of an electric locomotive accelerating a drawbar pull would have less tendency to slip than a steam locomotive accelerating that same pull.

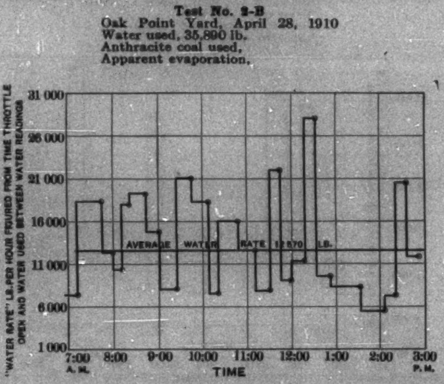

Test No. 2-B
Oak Point Yard, April 28, 1910
Water used, 35,890 lb.
Anthracite coal used,
Apparent evaporation,

FIG. 23.—Water and coal consumption on switch engine

Tables 2, 3, 4 and 5 and curves Figs. 20, 21, 22 and 23, for April 8, 13, 21 and 28, which, by the way, were taken at random show operating data as follows:

TABLE 2.

LOG OF TEST NO 1-A

HARLEM RIVER YARD ENGINE NO. 2392 APRIL 8, 1910

Time		Avg. boiler press	Throttle open		Engine in motion		Engine Standing		Total cars handled		Water lb.	Water rate lb. per hour
			M.	S.	M.	S.	M.	S.	L.	E.		
8:00	8:13	200.0	3	0	8	0	5	0	3	0	561.8	11,240
8:13	8:28	200.0	6	35	12	40	2	20	30	4	936.3	8,530
8:28	8:42	191.7	5	20	9	25	4	35	6	6	811.5	9,130
8:42	8:53	201.0	5	45	8	25	2	35	31	10	1935.0	20,190
8:53	9:10	197.5	5	50	9	25	7	35	2	3	811.5	8,350
9:10	9:23	196.7	6	35	10	10	2	50	16	0	1748.0	15,930
9:23	9:41	200.0	4	30	5	0	13	0	Note		749.0	9,990
9:41	10:13	198.0	9	35	15	30	16	30	23	0	1810.0	11,330
10:13	10:31	196.3	8	30	10	10	7	50	61	0	2184.0	15,420
10:31	10:51	190.0	12	40	18	10	1	50	28	35	2497.0	11,830
10:51	10:55	195.0	1	15	2	25	1	35	3	0	374.6	17,980
10:55	11:14	202.0	8	30	14	35	4	25	17	12	1748.0	12,340
11:14	11:27	202.5	3	15	4	30	8	30	6	6	624.0	11,520
11:27	11:40	201.0	8	00	9	0	4	0	19	13	2247.0	16,850
11:40	12:02	200.0	6	55	11	35	10	25	52	0	1997.0	17,320
12:02	12:15	201.7	3	10	5	45	7	15	17	0	1061.0	20,110
12:15	12:38	197.5	7	55	12	0	11	0	66	0	1311.0	9,940
12:38	12:58	199.0	8	0	12	50	7	10	15	57	1873.0	14,050
12:58	1:36	200.8	6	35	13	45	24	15	53	0	2747.0	25,030
1:36	1:53	200.0	3	20	7	10	9	50	23	0	1248.0	22,470
1:53	2:01	200.0	6	0	6	50	1	10	40	0	936.0	9,360
2:01	2:15	196.7	5	10	8	25	5	35	14	1	1186.0	13,770
2:15	2:34	200.0	4	50	7	50	11	10	20	0	1436.0	17,820
2:34	2:42	197.5	2	10	3	40	4	20	15	0	749.0	20,740
2:42	2:56	201.3	3	30	8	45	5	15	29	0	1623.0	27,820
2:56	3:20	200.0	5	35	10	55	13	5	26	0	1436.0	15,430
3:20	3:35	191.7	7	10	11	20	3	40	24	0	1935.0	16,200

Note—Pull car on track.

Total length of time of shift..........................7 hr. 35 min.
Total time throttle open..........................2 hr. 40 min. or 35% of total
Total time engine in motion..........................4 hr. 18 min. or 57% of total
Total time engine standing..........................3 hr. 17 min. or 43% of total
Total water used..........................38,600 lb.
Total anthracite coal fired.......................... 5,540 lb.
App. evaporation.......................... 6.98 lb. of water

Average rate of water used per hour, figured from water used and time throttle open between water readings, 14,500 lb. of water.

TABLE 3.

LOG OF TEST NO. 4-A

HARLEM RIVER YARD. ENGINE 2392. APRIL 13, 1910.

Time		Avg. boiler press	Throttle open		Engine in motion		Engine Standing		Total cars handled		Water lb.	Water rate lb. per hour
			M.	S.	M.	S.	M.	S.	L.	E.		
7:20	7:48	202.5	9	25	17	0	11	0	22	14	687	4,380
7:48	7:57	195.0	4	0	8	45		15	8	10	1061	15,910
7:57	8:14	199.3	8	55	12	45	4	15	26	27	1997	13,440
8:14	8:35	198.3	6	25	12	45	8	15	32	3	1311	12,260
8:35	8:40	200.0	2	15	2	40	2	20	9	7	874	23,300
8:40	8:56	200.0	5	25	10	55	5	5	21	13	1124	13,560
8:56	9:16	202.5	3	0	4	55	15	5	18	2	1061	21,220
9:16	9:24	195.0	5	30	6	10	1	50	38	2	1248	13,610
9:24	9:43	191.3	10	50	14	45	4	15	25	36	1685	9,330
9:43	9:57	198.8	5	50	11	40	2	20	17	23	1124	11,560
9:57	10:16	201.0	9	45	15	15	3	45	31	20	1623	9,990
10:16	10:32	200.0	5	45	12	0	4	0	7	9	2122	22,140
10:32	10:45	202.5	4	0	8	10	4	50	9	5	687	10,310
10:45	11:19	201.7	14	20	25	50	8	10	26	17	2746	11,490
11:19	11:26	195.0	4	30	16	10	1	0	4	1	437	5,830
11:26	11:48	195.0	9	45	19	15	2	45	26	19	1623	9,990
11:48	12:09	200.0	6	20	8	10	12	50	13	11	1436	13,600
12:09	12:25	199.0	7	10	11	20	4	40	20	29	1186	9,930
12:25	12:40	200.0	7	40	11	15	3	45	12	5	624	4,880
12:40	12:56	195.0	6	50	9	15	6	45	49	5	1373	12,060
12:56	1:15	192.5	8	50	14	20	4	40	18	12	1560	10,600
1:15	1:34	196.3	8	5	15	15	3	45	26	22	1248	9,260
1:34	1:49	192.5	6	10	10	35	4	25	14	15	936	9,110
1:49	2:00	200.0	4	20	5	25	5	35	9	7	1061	14,690
2:00	2:08	200.0	5	10	6	15	1	45	9	7	562	6,530
2:08	2:34	193.8	5	35	10	5	15	55	22	4	1311	14,100
2:34	2:53	191.3	8	50	14	15	4	45	39	4	1935	13,020
2:53	3:06	202.5	2	55	6	5	6	55	3	5	749	15,410
3:06	3:20	197.5	7	45	10	10	3	50	24	35	1810	14,010

Total length of time of shift..........................8 hr. 0 min.

Total time throttle open..........................3 hr. 15 min. or 40.6% of total

Total time engine in motion..........................5 hr. 21 min. or 66.9% of total

Total time engine standing..........................2 hr. 39 min. or 33.1% of total

Total water used..........................37,265 lb.

Total anthracite coal fired.......................... 5,500 lb.

Approximate evaporation..........................6.53 lb. of water.

Average rate of water used per hour, figured from water used and time throttle open between water readings—11,400 lb. of water.

TABLE 4.

LOG OF TEST NO. 8-A

HARLEM RIVER YARD. ENGINE 2392. APRIL 21, 1910.

Time		Avg. boiler press	Throttle open		Engine in motion		Engine Standing		Total cars handled		Water lb.	Water rate lb. per hour
			M.	S.	M.	S.	M.	S.	L.	E.		
7:30	8:03	195.0	10	50	19	45	13	15	11	20	1498	83,000
8:03	8:22	195.0	8	15	14	5	4	55	46	5	1685	12,250
8:22	8:42	200.0	7	10	14	15	5	45	12	9	1498	12,540
8:42	8:58	202.5	2	35	4	40	11	20	4	2	1311	30,490
8:58	9:16	189.0	11	20	14	35	3	25	20	38	1873	9,920
9:16	9:45	190.0	3	25	6	50	22	10	2	2	1748	30,660
9:45	10:01	196.7	5	10	15	30	0	30	9	9	1124	13,050
10:01	10:17	197.0	8	15	13	25	2	35	57	5	1248	9,080
10:17	10:36	197.5	9	0	14	20	4	40	16	18	1873	12,490
10:36	10:48	193.3	5	25	10	30	1	30	18	24	1186	13,140
10:48	11:09	190.0	8	5	12	45	8	15	57	5	1810	13,440
11:09	11:24	195.0	4	5	8	15	6	45	6	2	624	9,180
11:24	11:45	192.0	9	0	15	10	5	50	58	5	2247	14,980
11:45	12:06	194.0	13	35	16	35	4	25	24	37	1935	8,550
12:06	12:24	197.5	4	45	9	30	8	30	5	2	2310	20,180
12:24	12:54	193.3	12	40	24	10	5	50	11	4	1873	8,870
12:54	1:13	192.5	4	45	10	50	8	10	9	14	811	10,250
1:13	1:34	190.0	7	10	13	55	7	5	7	11	1561	13,070
1:34	1:51	192.5	7	15	14	25	2	35	6	18	1498	12,400
1:51	2:09	197.5	2	15	3	50	14	10	7	2	1311	34,960
2:09	2:46	197.0	12	10	22	10	14	50	29	5	3870	19,060
2:46	3:05	195.0	6	25	12	40	6	20	19	4	1498	13,990
3:05	3:20	192.5	7	15	13	20	1	40	25	49	1685	13,945
3:20	3:30	187.5	4	20	6	30	3	30	4	2	624	8,640

Total length of time of shift..........................8 hr. 0 min.
Total time throttle open..............................2 hr. 55 min. or 36.5% of total
Total time engine in motion..........................5 hr. 12 min. or 65.0% of total
Total time engine standing...........................2 hr. 48 min. or 35.0% of total
Total water used......................................38,700 lb.
Total anthracite coal fired...........................5,450 lb.
Approximate evaporation..............................7.10 lb.

Average rate of water used per hour, figured from water used and time throttle open between water readings—12,060 lb. of water.

TABLE 5.

LOG OF TEST NO. 2-B

OAK POINT YARD. ENGINE 2392. APRIL 28, 1910

Time		Avg. boiler press	Throttle open		Engine in motion		Engine Standing		Total cars handled		Water lb.	Water rate lb. per hour
			M.	S.	M.	S.	M.	S.	L.	E.		
6:54	7:11	198.0	7	10	11	55	5	5	24	35	874	7,320
7:11	7:44	191.7	4	40	9	5	23	55	3	6	1436	18,460
7:44	7:59	187.0	7	30	11	25	3	35	53	18	1561	12,490
7:59	8:10	176.7	5	0	9	40	1	20	10	17	874	10,490
8:10	8:22	180.0	5	10	7	0	5	0	10	13	1561	18,120
8:22	8:44	191.7	7	45	15	5	6	55	44	6	2497	19,330
8:44	9:01	185.0	7	5	12	40	4	20	29	35	1748	14,810
9:01	9:24	188.8	10	35	18	25	4	35	16	25	1436	8,140
9:24	9:45	191.7	2	40	5	20	15	40	22	3	936	21,060
9:45	10:08	190.0	7	10	10	30	12	30	22	3	2185	18,290
10:08	10:20	190.0	5	25	9	30	2	30	15	35	687	7,610
10:20	10:48	193.3	7	40	14	30	13	40	0	3	2060	16,120
10:48	11:10	177.5	10	45	16	40	5	20	30	16	2247	12,540
11:10	11:30	182.5	11	20	19	20	0	40	18	28	1498	7,930
11:30	11:45	195.0	3	45	9	5	5	55	8	3	1373	21,970
11:45	11:59	180.0	10	10	13	45	0	15	48	31	1561	9,210
11:59	12:18	181.3	6	15	12	5	6	55	2	10	1186	11,390
12:18	12:33	186.7	6	15	12	25	2	35	11	13	2934	28,170
12:33	12:52	173.3	11	15	15	50	3	10	10	20	1810	9,650
12:52	1:32	190.0	7	30	15	0	25	0	0	6	1061	8,490
1:32	2:05	190.0	8	10	12	35	20	25	3	8	749	5,500
2:05	2:20	187.5	7	10	10	40	4	20	3	6	874	7,320
2:20	2:35	198.3	4	0	7	20	7	40	4	8	1373	20,600
2:35	2:52	200.0	7	0	12	30	4	30	10	15	1373	11,770

Total length of shift..............7 hr. 58 min.
Total time throttle open..........2 hr. 51 min. or 35.8% of total time.
Total time engine in motion.......4 hr. 52 min. or 61.1% of total time.
Total time engine standing........3 hr. 6 min. or 38.9% of total time.
Total water used...............35,890 lb.
Average rate of water used per hour, figured from water used and time throttle open between water readings—12,570 lb. of water.

It is interesting to note the following averages:

1. Total time of throttle open.................36.7 per cent
2. Total time engine in motion................62.65 per cent
3. Total time engine standing.................37.5 per cent
4. Rate of water used per hour..............12633 lb.
5. Total water used—7.5 hours..............37603 lb.

By these figures and the curves plotted we are able to get a close approximation of the average energy required to be delivered to the drivers of a switching engine, and what its maximum requirements are. Particularly interesting is the water rate of 12,633 lb. Assuming 40 lb. of water evaporated per horse-power-hour, which is probably much lower than the actual, it is seen that the average horse power ***during the time the throttle is open*** is approximately 313 h.p.; but it is noted that the engine is developing power for only 36.7 per cent of the time, and thus the average energy developed during the hour is approximately 115 h.p. The reduction of the energy developed by a switching engine to an average of 115 h.p. has been something of a revelation to the writer, and the two most important things it suggests are:

1. That in switching, yard speeds can be greatly increased by the use of an electric switcher of very much less engine capacity than that used in the steam switcher.
2. On account of the low average rate of energy required for their operation, a central power station will deliver at far higher efficiency the power necessary to the electric switching engine, than that obtained from the power plant individual to the steam switching engine itself.

Immediate application of this statement is seen in the ratio of the pounds of coal burned to the number of horse power hours developed, which is seen to be 6.4. Increasing this by the coal burned during the idle hours of the engine, this ratio approximates 8. It has been demonstrated, that the ratio between the coal burned for operating passenger trains by electric, rather than steam locomotives, is 1 to 2. In the case of switching engines this rate is much greater; a figure of 1 to 3 being conservative.

STATISTICAL RECORD OF SINGLE-PHASE TRUNK LINE OPERATION

In the paper entitled "The Log of the New Haven Electrification", presented before the A.I.E.E., by the writer in December, 1908, there was given a table of train minute delays with their causes and a set of graphical charts supplementing them, which gave a very fair idea of the general character of the service resulting in the early days of operation shortly after the construction had been sufficiently advanced to permit a trial of full operation between Stamford and New York City.

In Figs. 24, 25, 26, 27, 28 and 29, herewith, are given similar data for operation covering a consecutive period of six months—one year later; the service having by that time settled down to something of a more commercial character.

For the sake of comparison, it is interesting to place these tables and charts of six months' operation in proximity to each other. The tables of train minute delays for 1908 and for 1909 are therefore presented in the same illustrations, each with the same scale.

Individual and collective train-minute delays between New York and Stamford

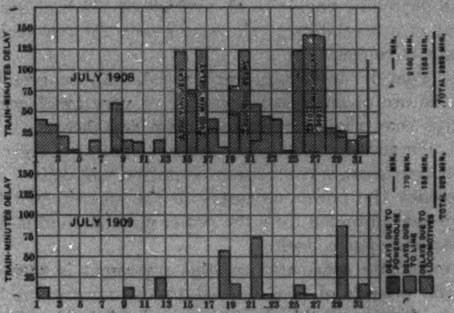


FIG. 24.—Train minute delays, July 1908–1909

Individual and collective train-minute delays between New York and Stamford

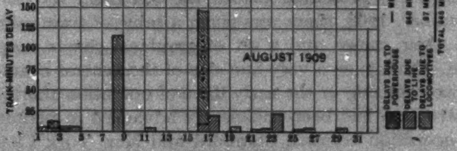


FIG. 25.—Train minute delays, August 1908–1909

Reproduced charts are inclusive of train minute delays over 300 minutes; which, for the reasons explained, were omitted by the author in his original paper.

The most interesting thing to note in these tables of more recent operation is the disappearance of delays, with the exception of one amounting to over 300 train minutes. The total train minute delays for the six months' consecutive operation in 1908 were 10,373 train minutes; and summing up the train minute delays for the six months' consecutive operation in 1909 we find the train minute delays to be 2,076. Thus, the train minute delays for the six months of 1909 were one-fifth of the train minute delays for 1908.

Individual and collective train-minute delays between New York and Stamford

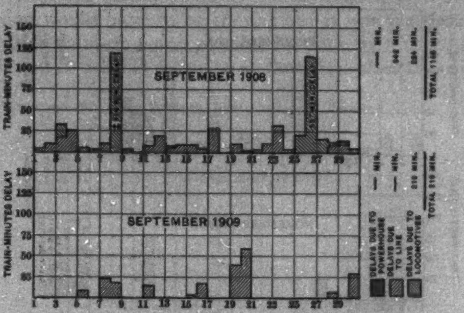


FIG. 26.—Train minute delays, September 1908–1909

Individual and collective train-minute delays between New York and Stamford

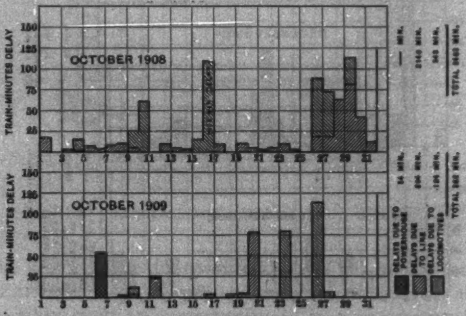


FIG. 27.—Train minute delays, October 1908–1909

In the summation sheet shown in Fig. 30 it is interesting to note as a more intimate acquaintance with the system's characteristics and a better knowledge of the details that needed correction or change were impressed upon us in the regular log of operation, the train minute delays steadily decreased, with the exception of one month (in October 1908) in which, as brought out in the author's previous paper, there was a serious power house delay, due to the explosion of an oil switch. The delays

Individual and collective train-minute delays between New York and Stamford

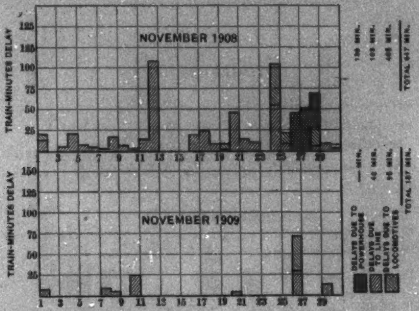


FIG. 28.—Train minute delays, November 1908–1909

Individual and collective train-minute delays between New York and Stamford

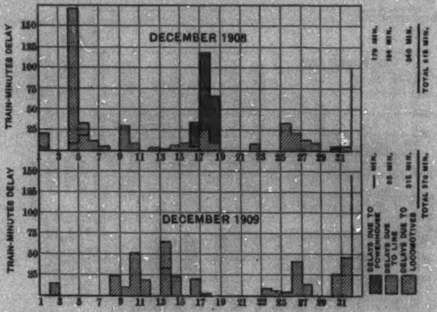


FIG. 29.—Train minute delays, December 1908–1909

as shown in the same figure for the six months of the year following show the system's stability of operation, and this was anticipated by those who had not composed its obituary in the early days of its first trial.

The author has been criticized by his engineering friends for having written the earlier paper at a time when so poor a record of operation would have to be shown; but it was his thought at the time that no harm could possibly be done by a revelation of the facts, and it was his estimate at that time that the criticism would be dissolved in the consideration of the actual facts that were contributary to the cause of the service rendered, and that later possibly such an opportunity as is now presented would arrive, when the justification of this stand could be sustained. Therefore, this record of operation one year after that presented in the original paper, is not offered in any sense as a proof of the reliability of service that can be produced by the single-phase system of train operation. This fact has been too plainly evident by the consensus of opinion expressed in the public and

Train minutes delay between New York and Stamford

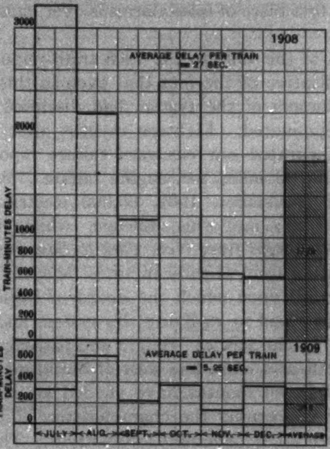


FIG. 30.—Tabular summation of train delays

technical press, indicating the satisfaction of the travelling public who have to use the New Haven electrification in their business. It is to be confessed by the author, however, that there is some personal satisfaction involved in making this invidious comparison between trial and practical operation, in recalling what some of my friendly sceptics had to say about our system, but in the same breath let me say that this is offered in no feelings of rancor or unfriendliness; on the contrary, this record of operation is presented with the hope that it may turn the thoughts of those former friends into the path, which before seemed such a difficult one in which to tread, the simplicity of which, after the first blare of false alarms is over, must now come into bold relief.

A comparison of the 1909 to the 1908 train minute delays is immediately indicative of the fact that even in this short time the disturbing factors of the system had disclosed themselves and had been eliminated. Eighteen months after commercial service was inaugurated our electrical failure report shows a record of over 15,700 miles per engine failure. Between the 2d and 23d of November, 1909, 66,000 electric locomotive miles were run off; and this mileage, which is approximately *eleven round-trips from New York to San Francisco*, was accomplished with a total of three minutes' delay. This kind of record is the ground upon which the Board of Directors of the New Haven road stood in ratifying the system and voting an extension to apply to all service—freight and passenger, inclusive of yards, terminals and main line west of Stamford.

These same eighteen months have yielded an abundance of new information concerning the characteristics of the system, inclusive of power house, line and locomotives. Though all of these departments contributed their share of train delays in our initial operation, the unlooked for troubles, which while not in any way fundamentally attacking the principles of the system, reflected upon it, for traffic delays are always a great factor in the public estimate, and have sometimes been misapplied as arguments against the system by those who should have discriminated between the incidental and the fundamental.

Comparison between Electric and Steam Operation. In Fig. 31 is an interesting relation between failures for trunk line service of electric *vs.* steam operation. As is to be noted in the lower diagram of the figure, the power house failures in its effect on engine mileage is practically nil. On account of the severe handicap that has been placed on the line by steam locomotive stack discharges directly beneath it, a number of failures per 100,000 engine miles are recorded. An elimination of the steam service under the electrified wires will greatly reduce, if not entirely eliminate, failures due to this part of the electrical system. In the upper diagram of the figure is shown the relation of electric engine mileage per failure *vs.* steam mileage. It is to be noted in this that the electric locomotive failures are nine per 100,000 electric engine miles, while the steam, which is an average figure for all of the divisions of the New Haven, is 21. Thus,

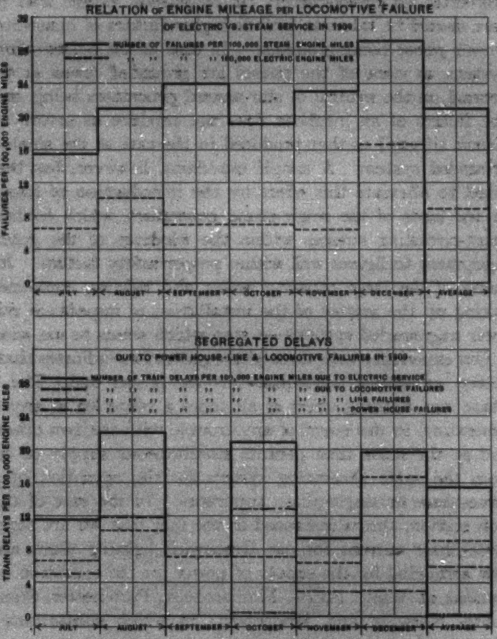


FIG. 31.—Relation engine mileage to failure

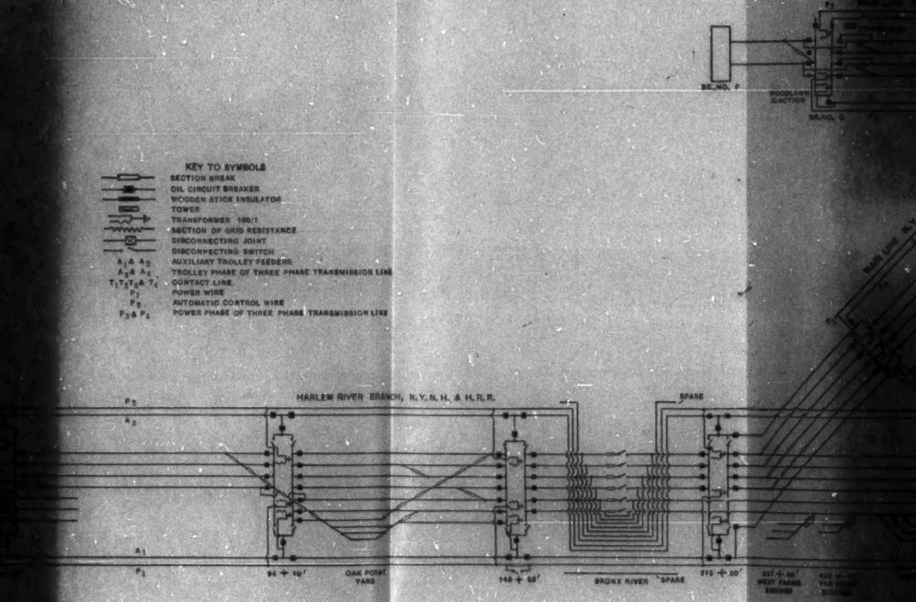
the electric locomotive service is 133 per cent better than the steam.

POWER HOUSE

The power house of a single-phase system does not differ essentially from the power house which generates high-voltage three-phase current for distribution to substations where it is converted for direct-current car propulsion, except that greater care should be taken to include higher factors of insulation, due to one phase being grounded. In case of the before-mentioned system, as none of the phases are grounded (even at times a ground on the neutral of star-wound generators being omitted) the failure of an insulator does not produce as severe a short circuit (if any) as that produced in the case of the single-phase grounded system. A simple expedient, however, has been devised to alleviate this effect by the introduction of impedance in the leads of the single-phase generators, which confines the short-circuiting stresses within the windings of the generating equipment to figures well within proper safety factors. Indeed, many of the large capacity power and lighting companies are taking up the matter of the installation of impedance coils for their ungrounded systems—a step which seems to me wise.

Our experience with three-phase generators indicates that their choice, as against single-phase, is the proper one. The three-phase star winding offers at all times a spare leg in any of the generators, in the event of any trouble with the two other legs; and at the same time permits simultaneous supply of current from the same generating system for the operation of either three-phase or single-phase apparatus. In the case of the Cos Cob station, this is instanced in the fact that we are supplying three-phase current for our Greenwich lighting plant and are now arranging for the supply of power for the operation of substations at White Plains, Mamaroneck, Portchester, Stamford, South Norwalk and Bridgeport; in which substations there will be operated motor-generator or synchronous converter outfits for the supply of direct current for railway purposes at the above mentioned places.

By the installation of copper-clad rotating fields in our generators, the unbalanced voltage between phases is reduced to a minimum, and such as remains is easily compensated for by arrangement of transformer taps in the substations reducing the three-phase current from high to low voltage for motor or synchronous converter application.


KEY TO SYMBOLS
SECTION BREAK
OIL CIRCUIT BREAKER
WOODEN STICK INSULATOR
TOWER
TRANSFORMER 100:1
SECTION OF GRID RESISTANCE
DISCONNECTING JOINT
DISCONNECTING SWITCH
A_1 & A_2 AUXILIARY TROLLEY FEEDERS
A_3 & A_4 TROLLEY PHASE OF THREE PHASE TRANSMISSION LINE
T_1 T_2 T_3 & T_4 CONTACT LINE
P_1 POWER WIRE
P_2 AUTOMATIC CONTROL WIRE
P_3 & P_4 POWER PHASE OF THREE PHASE TRANSMISSION LINE
HARLEM RIVER BRANCH, N.Y.N.H. & H.R.R.
P_2
A_2
A_1
P_1
94 + 10′
OAK POINT YARD
140 + 68′
SPARE
BRONX RIVER
SPARE
215 + 80′
237 + 80′ WEST FARMS SIDINGS
VAN NEST SIDINGS
BR. NO. F
WOODLAWN JUNCTION
BR. NO. 0
P_2
MAIN LINE
TOWER
A_1
MAIN LINE N.Y.
A_2
P_2

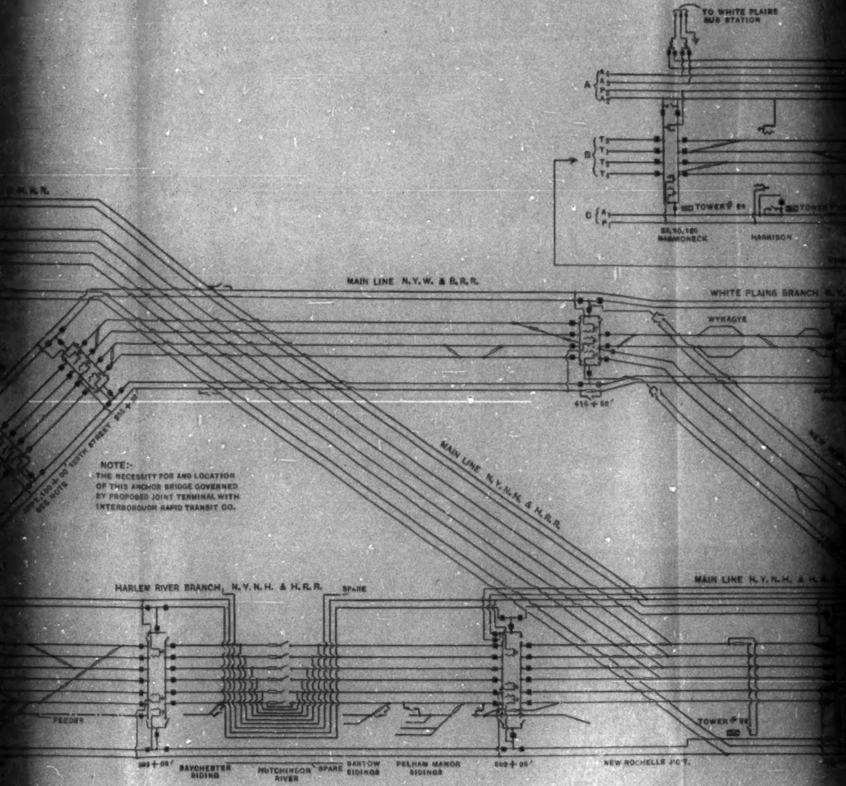
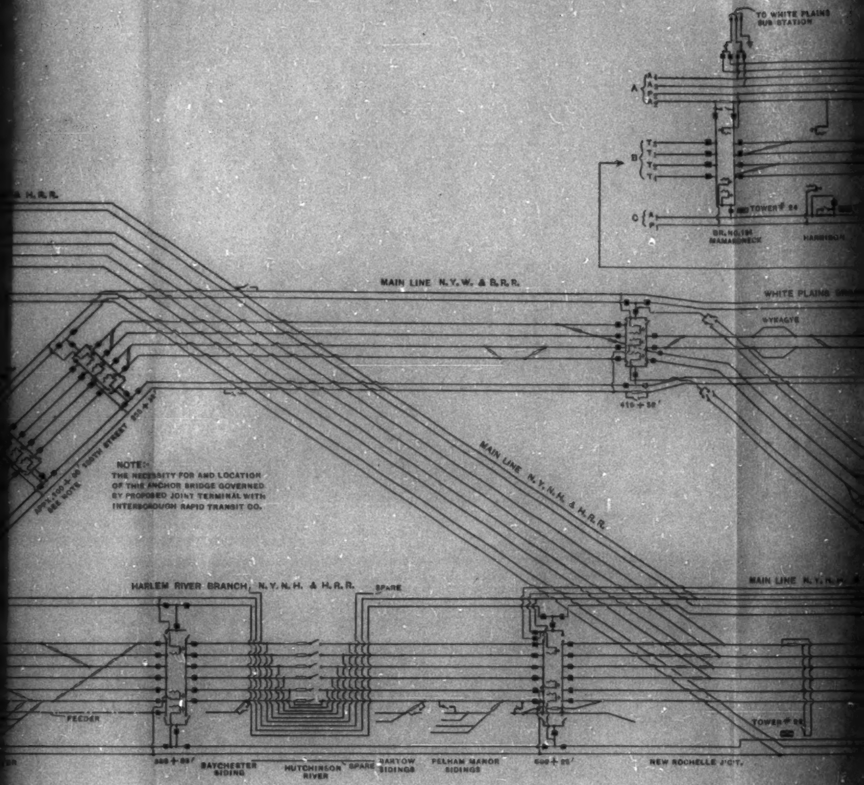
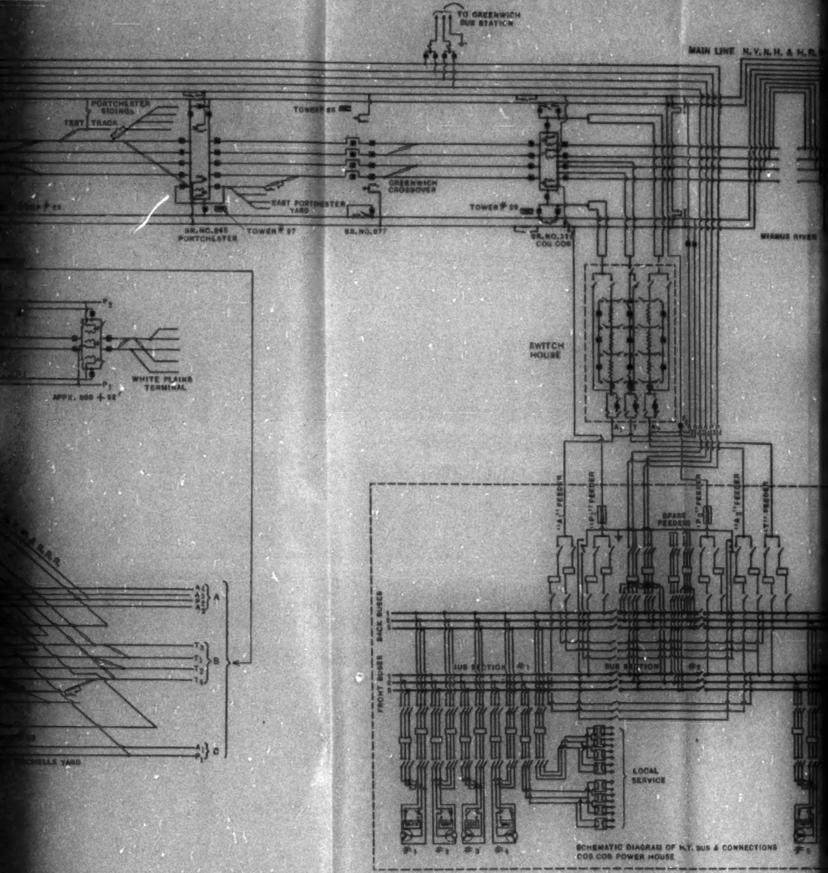

TO WHITE PLAINS SUB STATION
A
B
C
T
A
P
TOWER # 24
TOWER
MAMARONECK
HARRISON
N.H.R.R.
MAIN LINE N.Y.W. & B.R.R.
WHITE PLAINS BRANCH N.Y.W. & B.R.R.
WYKAGYE
416 + 50'
120TH STREET
SEE NOTE
NOTE:-
THE NECESSITY FOR AND LOCATION
OF THIS ANCHOR BRIDGE GOVERNED
BY PROPOSED JOINT TERMINAL WITH
INTERBOROUGH RAPID TRANSIT CO.
MAIN LINE N.Y.N.H. & H.R.R.
HARLEM RIVER BRANCH, N.Y.N.H. & H.R.R.
SPARE
MAIN LINE N.Y.N.H. & H.R.R.
FEEDER
BAYCHESTER SIDING
HUTCHINSON RIVER
SPARE
BARTOW SIDINGS
PELHAM MANOR SIDINGS
609 + 25'
NEW ROCHELLE JCT.
TOWER # 26

Fig. 32.—General wiring diagram of system


TO WHITE PLAINS SUB STATION
A
A 1
A 2
P 2
A 2
B
T 2
T 1
T 3
T 4
C
A
P
TOWER # 24
BR. NO. 1M MAMARONECK
HARRISON
& H.R.R.
MAIN LINE N.Y.W. & B.R.R.
WHITE PLAINS
WYKAGYE
410 + 50'
APPX. 100 + 00 SEE NOTE
180TH STREET
250 + 45
MAIN LINE N.Y.N.H. & H.R.R.
HARLEM RIVER BRANCH, N.Y.N.H. & H.R.R.
SPARE
FEEDER
MAIN LINE N.Y.N.H.
TOWER # 26
386 + 85'
BAYCHESTER SIDING
HUTCHINSON RIVER
SPARE
BARTOW SIDINGS
PELHAM MANOR SIDINGS
600 + 25'
NEW ROCHELLE J'C'T.

NOTE:-
THE NECESSITY FOR AND LOCATION OF THIS ANCHOR BRIDGE GOVERNED BY PROPOSED JOINT TERMINAL WITH INTERBOROUGH RAPID TRANSIT CO.

FIG. 32.—General wiring diagram of syst


TO GREENWICH SUB STATION
MAIN LINE N.Y.N.H. & H.R.
PORTCHESTER SIDINGS
TEST TRACK
TOWER # 28
TOWER # 26
GREENWICH CROSSOVER
EAST PORTCHESTER YARD
BR. NO. 245 PORTCHESTER
TOWER # 27
BR. NO. 277
TOWER # 29
BR. NO. 310 COS COB
MIANUS RIVER
SWITCH HOUSE
A₁
T
A₂
P₂
P₁
APPX. 860 + 92′
WHITE PLAINS TERMINAL
H. & B.R.R.
A₁
A₃
P₂
A₂
A
T₃
T₁
T₂
T₄
B
A₁
P₁
C
ROCHELLE YARD
"A₁" FEEDER
"P₁" FEEDER
SPARE FEEDERS
"P₂" FEEDER
"A₂" FEEDER
"T" FEEDER
BACK BUSES
FRONT BUSES
BUS SECTION #1
BUS SECTION #2
LOCAL SERVICE
#1
#2
#3
#4
#5
SCHEMATIC DIAGRAM OF H.T. BUS & CONNECTIONS COS COB POWER HOUSE

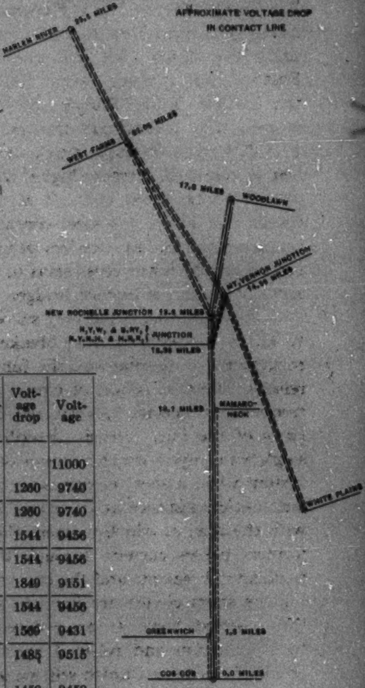
DISTRIBUTION SYSTEM

As indicated in the general wiring diagram of the system, Fig. 32, this is a unit system comprehending the main line of the New York New Haven & Hartford road between Stamford and Woodlawn, the six-track Harlem River freight and passenger connection from New Rochelle to the Harlem River Terminal., New York City and the New York, Westchester and Boston line running from the West Farms connection to the Harlem River Branch up to White Plains, N. Y. It is seen that throughout this extensive area, embracing in all over 300 miles of single track, there is not a single substation and no electrical pressure higher than 11,000 volts is used. It is further to be noted that all of the copper installed over the tracks just above the steel contact wire is in the same phase unaugmented by any feeders other than the by-pass wires installed on the lower cross-arms of the catenary posts to permit sectionalization of anchor bridges.

Of interest, also, is the very successful control system common to all of the sectionalizing breakers throughout this triple arrangement of distribution, the function of which is to insure a reliable selective action of circuit breakers to confine any line trouble to its specific locality, and thus making immune all other parts of the line. Briefly described, the control consists of a single wire, upon which is impressed the normal voltage of the system when a short circuit occurs anywhere, but not until the automatic resistance at the power station has been cut in series with the line; at which moment the control wire through transformers passes current through the tripping coils of the sectionalizing breakers, and the two breakers that are directly feeding the short circuit are immediately opened. The resistance, thus inserted, however, has reduced the short-circuiting current to a minimum and relieved greatly the duty of the opening breakers. The resistance scheme above mentioned, has proved itself to be a most valuable acquisition to the system, serving at once to lessen the duty on both generating and distributing apparatus.

The Reach of System. In Fig. 33 is shown the route arrangement of the three combined main lines—the New York New Haven and Hartford, the New York Westchester & Boston and the Harlem River Branch.

In the aforementioned, the first comprises a route of four tracks, the second a combination of four and two tracks, and the


APPROXIMATE VOLTAGE DROP
IN CONTACT LINE
HARLEM RIVER
25.5 MILES
WEST FARMS
21.05 MILES
17.6 MILES
WOODLAWN
MT. VERNON JUNCTION
14.95 MILES
NEW ROCHELLE JUNCTION 13.6 MILES
N.Y.W. & B.RY.
N.Y.N.H. & H.R.R.
JUNCTION
12.36 MILES
10.1 MILES
MAMARONECK
WHITE PLAINS
GREENWICH
1.5 MILES
COS COB
0.0 MILES

	Cross section		Voltage drop	Voltage
	Catenary	Feeder		
Cos Cob	4/0000	4/0000		11000
Mamaroneck			1260	9740
Marmaroneck	4/0000	4/0000	1260	9740
New Rochelle			1544	9456
New Rochelle	6/0000	2/0000	1544	9456
Harlem River	4/0000		1849	9151
New Rochelle	4/0000	2/00	1544	9456
Woodlawn			1569	9431
N. Y. W. & B. Ry. Junct.	2/0000	4/0000	1485	9515
N .Y. N. H. & H. R.R. Mount Vernon			1450	9450
Mount Vernon	4/0000	2/0000	1450	9450
West Farms			1725	9275
Mount Vernon	2/0000	2/0000	1450	9450
White Plains			1730	9270

FIG. 33.—Approximate voltage drop and route diagram.

third six tracks. Depending upon the number of tracks, there is provided always a varying conducting capacity of the over head wires and return rails. Throughout there is installed over each track one 4/0 copper conducting wire and one 4/0 steel contact wire; the latter suspended from the former by metallic clips. For future calculations it is essentially necessary to note the transmission characteristics of the overhead and track circuits, and to that end a very careful investigation was made to determine the constants of resistance of overhead wires and rail return, their individual and mutual reactance and the resultant impedance of these two right-angular drop-producing components.

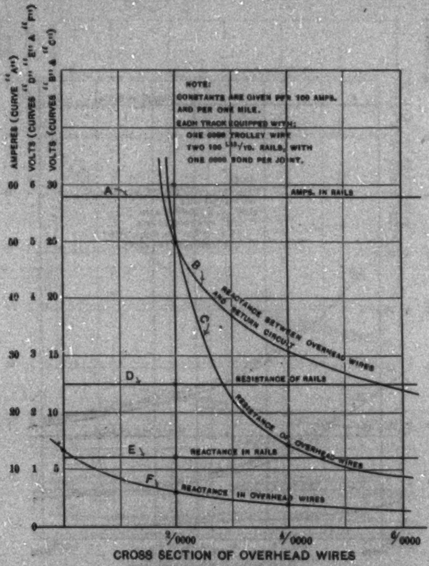


FIG. 34.—Constants for two-track equipment

The constants were worked out for two, four and six tracks and the curves of Figs. 34, 35 and 36 are the graphical result of the investigation.

It is interesting to note what the maximum drop on the system may be for conditions of peak load, and applying the constants as given by the curves it is seen that under maximum supply of power from Cos Cob station (during the 5:30 afternoon suburban load peak) the voltage at Harlem River Station, which is 25.6 miles from Cos Cob, is 9,151 volts—entirely sufficient to maintain all passenger and freight trains on schedule and to furnish at the same time the necessary power to switching engines doing duty on 100 miles of classification and switching yard tracks, which are a part of the Harlem River Branch electrification, and which are located most remotely from the power house.

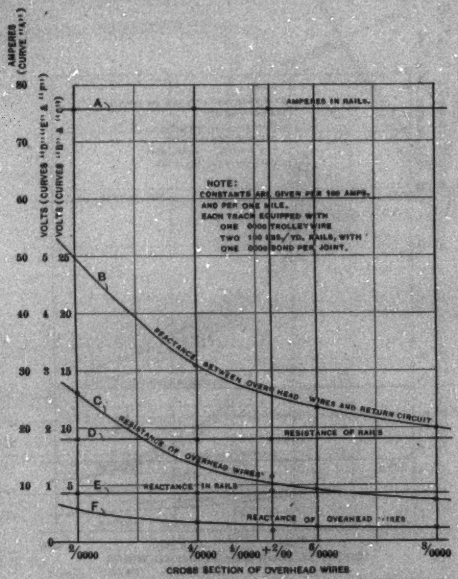


FIG. 35.—Constants for four-track equipment

Here, therefore, we see on a great scale history repeating itself, for it has ever been true where a large quantity of power and distance of transmission are combined, alternating current has been the chosen agent of transfer.

Voltage Regulation. The maximum conditions of peak load obtain on the so-called "Football Day" (when Yale University plays either Princeton or Harvard at New Haven). On November 19, 1910 the maximum peak at the power house for this day was 16,000 kw. Fig. 37 gives an all-day voltage chart showing synchronous clock-recording voltmeters registering the potential in three places—the power house, Mamaroneck tower and Mt. Vernon Tower; the latter being the junction of the New Haven with the New York Central Electrification (18 miles from the New Haven Power Station). In the morning hours the trains are dispatched to New Haven with a considerable more

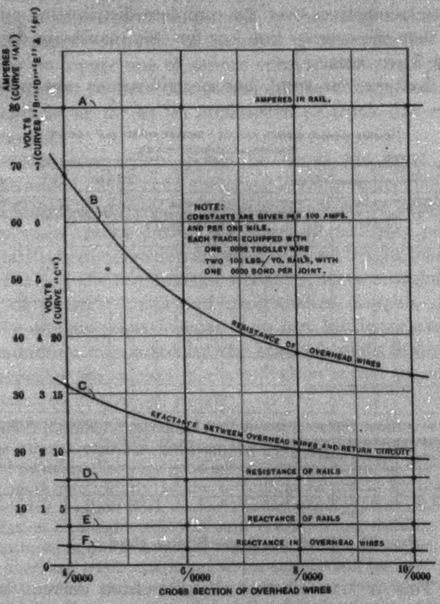


FIG. 36.—Constants for six-track equipment

headway than the same returning trains at night. This is indicated by the heavier drop in voltage due to the concentration of the evening load between the hours of 5:00 and 9:00. It is thus seen that the maximum line drop for this extraordinary day at the *end* of the line is 14 per cent; that the average drop at the *end* of the line is 4 per cent. Taking 75 per cent of this average drop at the *end* of the line for the general transmission of power to locomotives over the complete distributing system, it is seen that the average line loss for this maximum day was practically 3 per cent.

Storage batteries for trunk line electrifications are not economical. This is true whether the propulsion current be direct or alternating. It is true that the storage battery does smooth out the power station load and lowers the rate of cost of producing a kilowatt-hour, but the thing that concerns us quite as much as the rate of cost is the total amount of kilowatt-hours manufactured in payment for the luxury of the battery. A train service requires a certain number of kilowatt-hours. A plant producing these kilowatt-hours will be required to manufacture more energy with than without a battery on its distributing system.

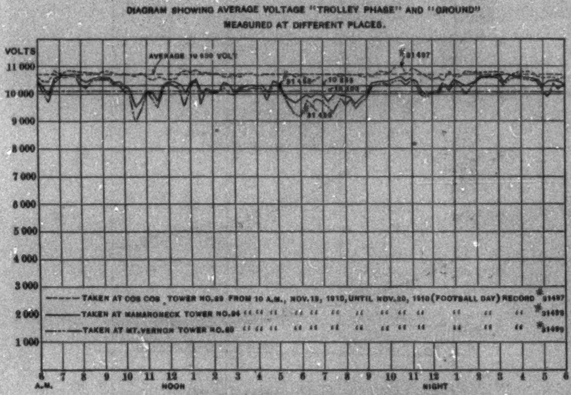


FIG. 37.—Drop on lines—Bristol chart

In general it may be stated that more kilowatt-hours means more coal, if the efficiency of generation is the same. As a matter of fact, the efficiency of electric energy production is higher with than without the battery, on account of the greater constancy of load for the former conditions, but the difference is so small that it is, at least for trunk line conditions, offset by the increase of output required and the cost of maintenance of the battery. On account of the established reliability of generating equipment the argument for the use of a storage battery for the supply of power in the event of power station breakdown is now no longer one of serious consideration, and so I think it is of interest to note the passing of the storage battery theory; at least in as far as its application to trunk line conditions is concerned.

In this connection should be noted the great importance of the added freight and switching loads in improving the station load factor, due both to the physical exclusion of freight trains from main tracks during the hours of passenger peaks and to the latitude of operation afforded in fixing freight schedules; thus discharging the functions of a battery, while escaping the penalties of battery losses and maintenance charges. Bearing directly on this point I quote from Mr. McHenry's report to the Commission appointed by the Massachusetts State Legislature to consider the subject of electrification within the Metropolitan District of Boston as follows:

> Power stations if provided for passenger requirements only, will have a large unused capacity between the hours of peak load, which otherwise could be utilized to very good advantage for the transportation of freight, and more particularly as the occupation of tracks by passenger trains during the hours of peak load acts automatically to limit the simultaneous operation of freight trains at such times. Thus, little or no additional investment in power houses is required to freight operation, and similarly the overhead track equipment serves equally well for both passenger and freight traffic, which makes it practicable to extend electric operation to include all classes of service at the cost of only the additional engines and the equipment of yard trackage required for freight service.
>
> It therefore seems quite safe to conclude that no general substitution of electric for steam traction should be made unless the substitution is complete, including passenger and freight operation and yard switching in addition, and also that in making such substitution the operation should be extended to include the full length of run or engine district, in order to avoid the uneconomical subdivision of the present " train runs ", together with the added expense and delays incident to intermediate engine transfer stations.

Insulation. There are points in the overhead system where the factor of insulation should be higher than at others. Practice has shown the wisdom of sectionalizing the lines at cross-overs. At these points it is necessary to bring the electrical catenary cables to a dead end and anchor bridges are supplied for that purpose. Oil switches must be provided for cutting in or out, as necessity may require, voltage on the lines thus dead-ended. In the order of their higher degree of insulation, requirements, I would mention:

1. Sectionalizing switches
2. Sectionalizing bus-bars.
3. Dead-end catenary insulators.
4. Intermediate catenary insulators.

As can be seen in the wiring diagram of the system Fig. 32 the whole track system leads into the anchor bridge buses, and a ground on them means an immediate effect on any wire connected to them. This reasoning is applicable to the switch, should the ground be on the bus bar side, and as the switch is a piece of moving apparatus, it is the more difficult to insulate and to keep insulated, and is therefore cited as the one deserving of the highest consideration of insulation.

The dead-end insulator has been mentioned third; let it be thoroughly understood, however, that it is in a class essentially its own, and worthy of respectful attention. No insulator throughout the past four years has had our more constant study. The difference between insulators not under and under mechanical strain while performing at the same time their electrical duty is marked. When the New Haven electrification was completed in 1908 the best dead-end insulator then on the market, and there were many firms competing, was one rated at 7,000 lb. mechanically and 40,000 volts electrically, and cost $27.00. We found in a very short time that two of these had to be used in series, which with the yoke harness made the cost $61. It is interesting to note here that in order to secure an insulator strong enough mechanically to withstand a cross catenary span in the electrification of our Portchester yard we had to design a yoke to hold two of the above insulators in multiple. To-day we have placed orders for dead-end (or strain) insulators, everyone of which is tested before shipment for 110,000 volts under a mechanical strain of 35,000 lb., and they have an ultimate mechanical tensile strength of 50,000 lb. The greatest credit is due the manufacturing companies who have developed this part of the art to this magnificent result. Indeed, the whole success of the high-voltage contact system depended upon such an attainment; and I can say, that I no longer have any moments of anxiety on this score, and consider that any further advance will be principally along the line of economy in manufacture. The insulator above described retails at $7, instead of $61; is capable of withstanding seven times the ultimate mechanical strength and three times the electrical strain of the original. This, in the vernacular of our American language, I think, is "some progress".

Steel Contact Wire. It is difficult to place sufficient emphasis on the importance and value of the steel contact wire which was suggested by Mr. McHenry and put in service on the New Haven Lines in 1908. Its adoption accords with the general practice represented in bridge construction. Previous to its adoption we had practically been running on the members, rather than the floor of our electrical suspension bridge. Every highway bridge, from the smallest to the largest, carries inexpensive and replaceable floor material. Likewise, now, in our catenary bridge, its floor is inexpensive and replaceable. Its members (electrical conductors) are not being weakened and its floor, though cheap in first cost, has a long life. Interesting figures to bring out the life of this floor are given in table 6 that follows, showing micrometer measurements of the steel wire taken at a point of maximum wear directly in front of one of our low highway bridges where the steel wire is on a gradient of 2 per cent; thus assuring a maximum upward vertical force of contact with the pantagraph shoe of the locomotive. It is interesting to note from these readings that the actual vertical wear of the wire since its first installation thirty months ago, is .028 in., which is practically 4.5 per cent per year of the half diameter of the wire (one half taken to permit wire to be held in clips) which, even on this vertical diameter basis, indicates a life of over twenty years; but as a matter of fact it will be much more than this, for the reason that as the vertical diameter lessens the breadth of contact increases throughout, thus diminishing the rate of vertical wear. Of further interest, too, is the fact that there is practically no corrosion on the wire; for, like the traffic rails in service (only much more so) the wire is constantly covered by a film of grease—due to a generous amount of this material being placed on the pantagraph shoe.

The steel wire is, in effect, a longitudinal spring of constant length, in which the tension only varies with the temperature. The coefficient of expansion of the contact wire and its sup-

TABLE 6.

VERTICAL MEASUREMENTS OF TROLLEY WIRE ON TRACK NO. 3

Diameter in inches

	9/3/08	12/10/08	2/17/09	12/15/09	2/26/11
Bridge 245	0.483	0.475	—	0.487	0.486
Center of span	0.484	0.480	0.487	0.483	0.467
Bridge 244	0.486	0.483	0.484	0.481	0.444
Bridge 238	0.487	0.483	0.483	0.478	0.475
Center of span	0.476	0.483	0.480	0.458	0.440
Bridge 237	0.483	0.474	0.475	0.462	0.443
Bridge 231	0.486	0.486	0.482	0.472	0.453
East approach Low bridge 40	0.483	0.478	0.477	0.459	0.429
Center approach Low bridge 40	0.479	0.473	0.471	0.443	0.422
West approach Low bridge 40	0.478	0.447	0.476	0.445	0.423
Bridge 230	0.484	0.470	0.474	0.470	0.457
Bridge 226	0.482	0.479	0.478	0.461	0.444
Center of span	0.483	0.472	0.476	0.457	0.425
Bridge 225	0.480	0.478	0.476	0.453	0.430
Bridge 222	0.478	0.481	0.472	0.470	0.445
Center of span	0.487	0.481	0.456	0.462	0.429
Bridge 221	0.490	0.489	0.496	0.461	0.450
Bridge 214	0.484	0.484	0.479	0.475	0.467
Center of span	0.484	0.469	0.477	0.441	0.432
Bridge 213	0.472	0.467	0.470	0.460	0.455
Bridge 160	0.476	0.470	0.471	0.466	0.462
East approach Low bridge 27	0.475	0.480	0.466	0.463	0.463
Center of low bridge	0.469	0.474	0.474	0.467	0.432
West approach low bridge	0.476	0.469	0.465	0.466	0.446
Bridge 159	0.478	0.475	0.478	0.472	0.464
Bridge 150	0.471	0.470	0.467	0.460	0.459
East approach Low bridge 25	0.471	0.478	0.480	0.474	0.469
Center of low bridge	0.480	0.477	0.470	0.472	0.465
West approach to Low bridge	0.476	0.477	0.476	0.477	0.468
Bridge 149	0.486	0.475	0.472	0.474	0.468
Bridge 147	0.501	0.508	0.504	0.500	0.493
East approach low bridge (24)	0.478	0.476	0.490	0.482	0.471
Center of low bridge	0.502	0.500	0.492	0.489	0.465
West approach low bridge	0.503	0.498	0.505	0.491	0.490
Bridge 146	0.486	0.491	0.488	0.479	0.478
Center of span	0.492	0.488	0.489	0.485	0.482
Bridge 145	0.496	0.498	0.485	0.483	0.478
Bridge 142	0.472	0.474	0.474	0.466	0.457
Bridge 137	0.471	0.474	0.469	0.465	0.462
Center of span	0.472	0.475	0.469	0.466	0.460
Bridge 136	0.478	0.480	0.478	0.474	0.472

porting catenary cable being the same, the difficult and objectionable adjustments which are incident to a combination of copper and steel are avoided.

It was thought, that the extreme variations in temperature might cause the contact wire to break, but this feature, happily, has not manifested itself. Our experience with this steel wire justifies its presence, and it will be used throughout our catenary construction over the New York, New Haven and Hartford, Harlem River Branch and the New York, Westchester & Boston electrification; thus serving something over 300 miles, measured in single track.

Electric Locomotives

In the writer's previous paper there was given a list of mechanical and electrical changes that were being made in the New York, New Haven and Hartford passenger type of locomotive and in the two years past an excellent opportunity has afforded to observe the result. No better index of the result could be evidenced than by the train minute delay statistics for six months of consecutive operation previously cited. As is always the case, new designs and practices include theoretical features which in practice are generally transformed into nuisances. The New Haven locomotives were no exception to this rule. Handicapped by the imposed condition of interchangeable operation on alternating- and direct-current systems—even with this complication to start with—to-day a closer inspection of the actually necessary control shows great simplification. The simplicity of the straight alternating-current single-phase control above all others can hardly be argued.

The introduction of a completely cushioned locomotive (with the exception of the wheels and axles) on heavy trunk line rails was one of keen interest to the maintenance-of-way department, and a careful study of its effect is being made. They have already reported a decided betterment of rail life and alignment since its introduction. Indeed it is not difficult to appreciate this natural result, due to the absorption of wheel impacts by the locomotive springs rather than by the track. In the quill spring arrangement as installed on the first New Haven locomotive the actual impact forces were under-estimated and the quantities of helical springs broken gave ample evidence of the deleterious forces at work. A much stronger set of helical springs was the answer. The quill drive with its various arrangements of spring support, by helical, tangential or other method, must answer to the charge of placing a greater first cost on the locomotives. The real question involved, is whether the interest on this cost and maintenance charges will offset the cost of repairs to track and equipment. There is abundant evidence in our hands to prove that it will do so many times.

The initial installation of the New Haven road provided for locomotive propulsion of all trains. This provision has proved wise, in view of the schedule requirements permitting this type of equipment, and during the past two years close attention has been given to the development of three other classes of equipment, namely: the multiple-unit train, the road freight engine and the switching engine. In the paper previously referred to, the passenger locomotive was discussed.

In Figs. 38 and 39 are shown the run curves as obtained from electric passenger locomotive 038, a locomotive typical of the original 41 ordered for express and local service between Stamford and Woodlawn. Fig. 38 has for its abscissae reference the time. In order, however, to bring out the relation of grade to power, Fig. 39 uses for its abscissæ the station location, with grade co-ordinated with it. In this figure the effect of grade on the required input of locomotive is very remarkably brought out.

In express train No. 9 it is to be noted that locomotive 038 is handling a train weighing 475 tons; the maximum weight mentioned in specifications for purchase of these locomotives was 250 tons. The trailing weight of this train was 377 tons; thus the weight carried is 50 per cent in excess of specification.

In the case of the local passenger train No. 213, it is to be noted that its weight is 316 tons, giving a trailing load of 214. For local service a maximum trailing load of 200 tons was specified, but it is to be noted by the areas plotted for kilowatt input that the locomotive is very much underloaded. The choice of train weights in these two tests was at random, and the tests conducted were upon trains in commercial service.

In the case of the passenger runs, the stations between Stamford and Woodlawn being spaced very much closer than between Stamford and New Haven, did not permit as economical operation as in the case of the latter, due to the fact that acceleration is maintained nearly up to the point of braking in each case. A greater station spacing would have permitted more coasting, and thus a higher rate of economy in watt-hours per ton-mile. The use, however, of locomotives

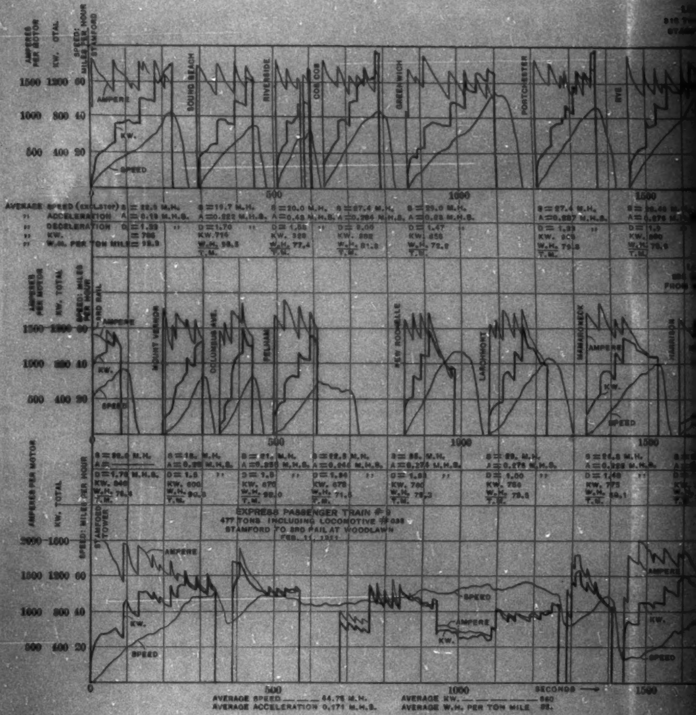
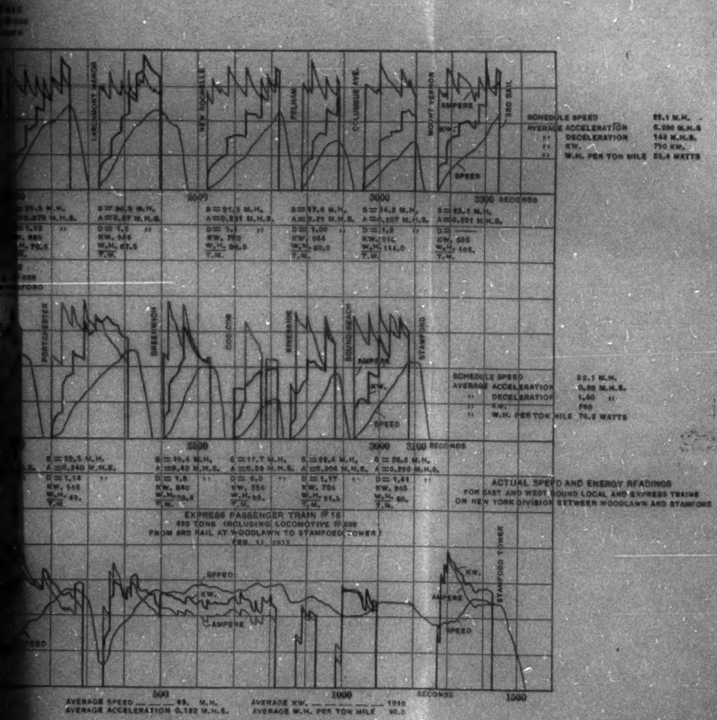


FIG. 38.—Actual speed and energy



west bound local and express trains

(Murray 1428.)

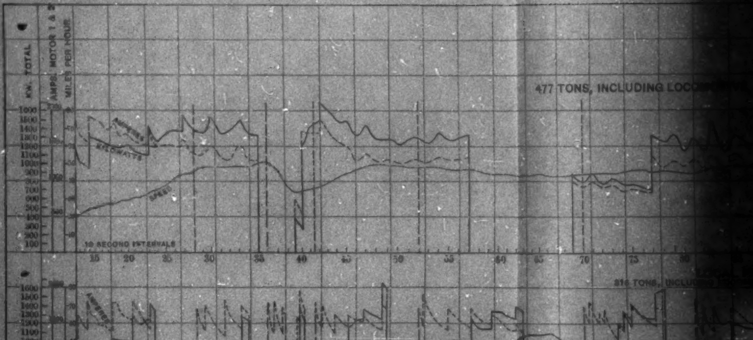
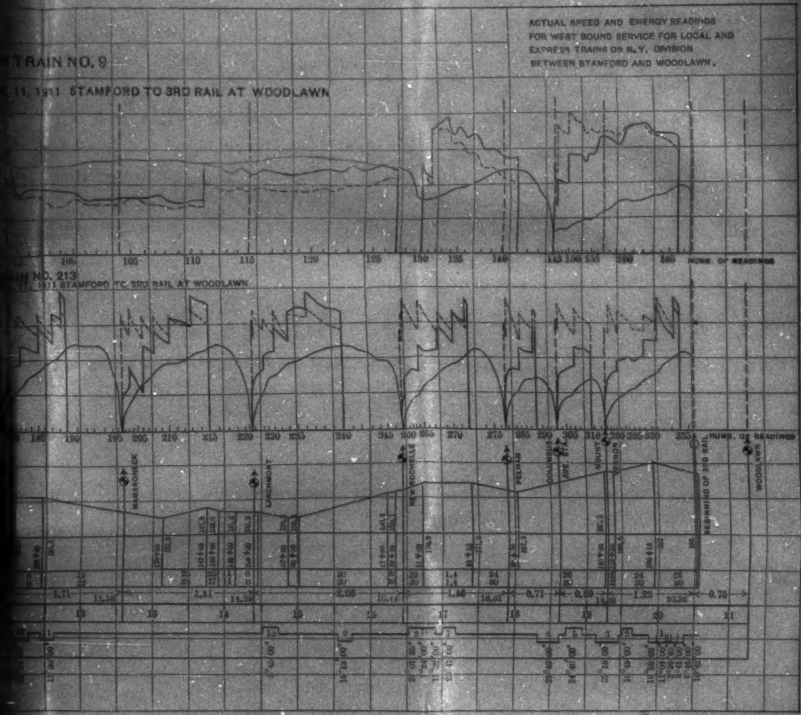
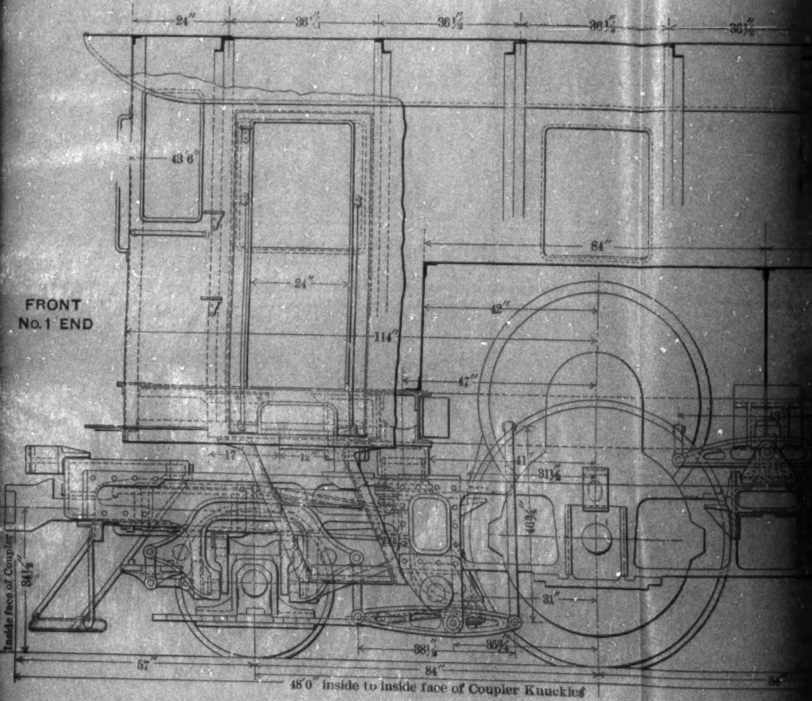


FIG. 39.—Actual speed and ener



est bound service for local and express

(Murray 1428a.)


24"
36½"
36½"
36½"
36½"
43'6"
FRONT
No. 1 END
24"
114"
84"
42"
47"
17
12"
41"
31⅛"
46¾"
31"
34½"
Inside face of Coupler
38⅛"
35¼"
57"
84"
84"
48'0" inside to inside face of Coupler Knuckles

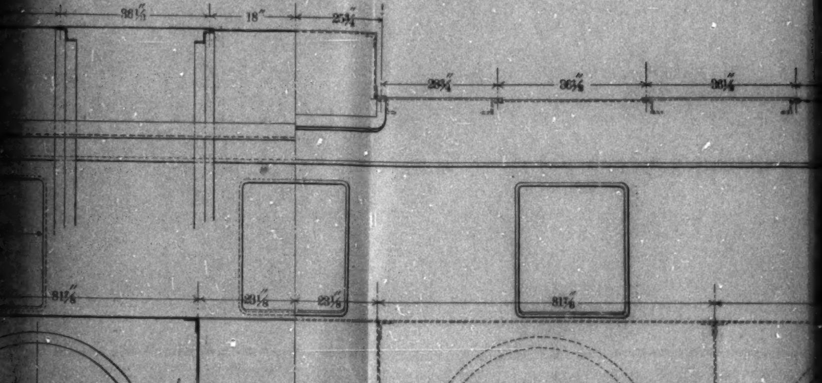
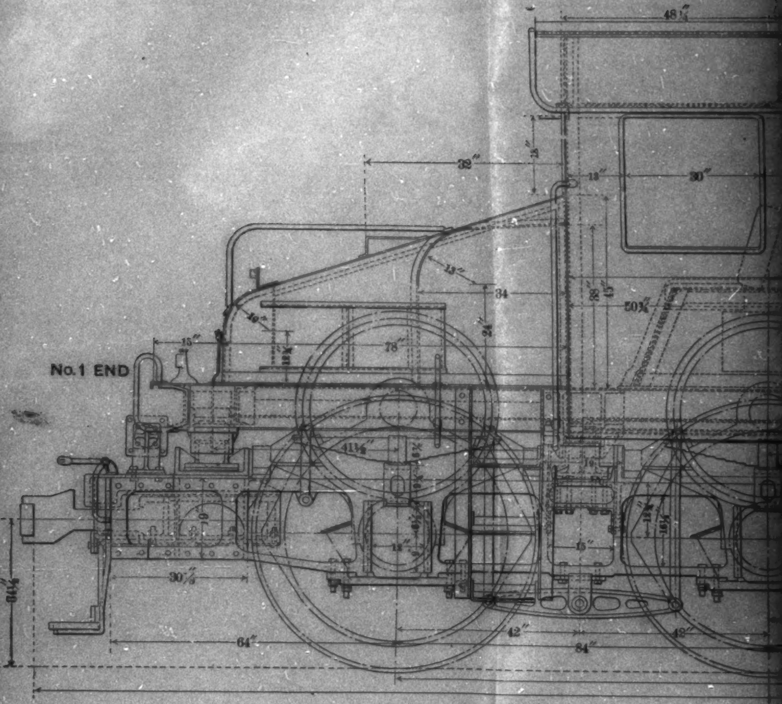
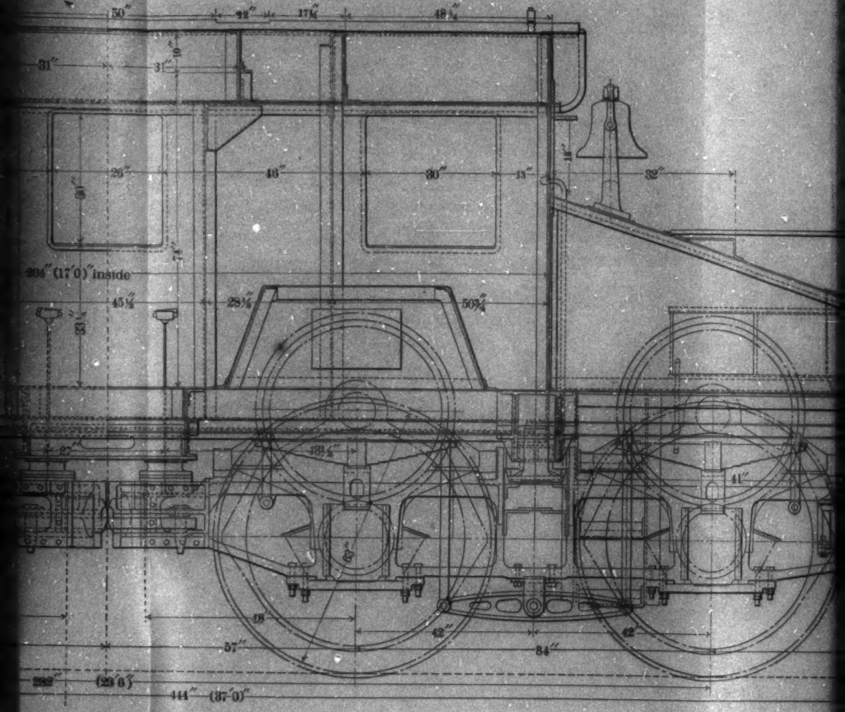

38½"
18"
25¾"
28¾"
36¼"
36¼"
81⅛"
23⅛"
23⅛"
81⅛"
41"
13⅝"
38"
21¼"
68"
68"
84"

Fig. 40.—Road freight engine


No.1 END
48¼"
32"
18"
13"
30"
13"
34
32"
15"
50¾
10"
15"
78"
24"
41⅛"
30⅝"
64"
42"
84"
42"
84⅛"
13"
15"


50"
12"
17⅞"
18¼"
10"
31"
31"
26"
46"
30"
13"
32"
18"
31"
204" (17'0") inside
74"
45½
28¼
50¾"
33½"
18½"
41"
27"
63"
48"
42"
42"
57"
84"
282"
(23'6")
444"
(37'0")

1.—Switching engine

for the local service was a wise provision, because at the time the electric service on the New Haven was inaugurated the single-phase multiple-unit equipment had not been sufficiently developed. The future will see the gradual replacement of the locomotives by multiple unit cars for suburban service, and the continued use of the locomotives thus replaced in the express service. Thus, in the event of the extension of the electrification to New Haven there will be a large credit on the work, in that the present locomotives will be used for express operation between New York and New Haven.

Again, these curves (both in express and local service) bring out, through the means of electrical units of power, the track resistances and engine power requirements as were indicated by the steam tests reproduced in the earlier part of the paper.

Space does not permit the inclusion of many drawings or a lengthy discussion of these three types of equipment. Fig. 40 gives an elevation drawing of our most recently designed freight locomotive, the electrical characteristics of which have been referred to in a previous part of this paper. One of the impressive characteristics of this engine is, its ability to start very heavy trailing loads; *e.g.*, 2160 tons. This, the largest load we were able to assemble, was easily accelerated. Such a torque bearing characteristic is of much value under conditions of acceleration on grade, but these figures must not be interpreted to mean that a tractive effort of this character can be sustained, except for a very short interval.

The locomotive is of the quill geared type, entirely spring supported (except wheels and axles), with pony wheels leading and trailing, and four propulsion motors are provided with a normal hourly rating of 396 h.p. each. The speed torque characteristics of the locomotive are shown in Fig. 17.

This type of locomotive is of higher power and differs from our present passenger engine in the arrangement of its apparatus, it being fitted with a central truck over superimposed motors, with the control apparatus arranged in the middle of the cab and a full passage on each side, giving excellent light for inspection of the various items of equipment. This is a marked improvement over the previous type of locomotive, the apparatus and control of which is arranged on the sides of the locomotive with a central aisle.

Besides the above described type of electric road engine, there is being built for the New Haven road two other types of equivalent hauling capacity; one of the side-rod design with two-motor equipment, the other having its power divided between eight motors. Much discussion (pro and con) on various types of engines typified in the above description lead the New Haven officials to a trial of engines of these different designs; all of them being entirely effective for the purposes to which they will be assigned, and at the same time offering a practical investigation into their individual merit, and thus permitting in the end a composite locomotive which will include, as far as possible, all the good principles, to the exclusion of the less desirable.

In connection with the above described locomotives, it is to be remembered also that they have all been designed inclusive of interchangeable operation on alternating current and direct current. In every instance this condition has increased weight and complicated control. A striking example of this is in the complete freedom from complication by the elimination of all direct-current considerations in the Hoosac Tunnel electrification. One is immediately impressed with the great simplicity of the single-phase Hoosac Tunnel locomotive when entering its cab immediately after a departure from a New York, New Haven and Hartford engine.

The cause of the above complication has been due to its having been deemed expedient for the handling of our heavier passenger trains that these electric freight road engines be equipped for direct-current operation from Grand Central Station, but fortunately only a few will be required; the remaining locomotives will be equipped for the simple straight single-phase operation and will haul freight trains between Harlem River and New Haven.

Fig. 41 gives an outline elevation drawing of our switching locomotive. This engine is coming to us as this paper goes to press. To the writer, it is the most interesting of all, though small and apparently insignificant. Much of our experience in electric locomotive practice has been of real value in the design of this engine. Like its larger brothers, it too is of the quill spring-supported type. On account of the buffing strains incident to yard work, its framing and the assemblement of equipment is made particularly substantial. The fact that the capacity of its motors (600 h.p., hour rating) will unquestionably measure up, and with considerable margin, to the duties to be imposed upon it, is brought out by the analysis of the steam switching requirements shown in the earlier part of this paper.

Already the Stamford yard (containing 4.2 miles of track) has been electrified, and upon receipt of the locomotive it will be exercised therein for commercial investigation.

In connection with our alternating-current multiple-unit train development, we have had in operation a multiple-unit equipment consisting of four motor cars and six trailers. Again the requirement of direct-current operation has superimposed upon this equipment the handicap of extra weight and complication of control, and, as in the instance of the locomotives, a careful investigation of the actual requirements necessary has served to reduce greatly these two unwelcome elements. Marked indeed in all types of propulsion apparatus, is the relative simplicity of straight single-phase, over alternating-current-direct-

TABLE 7.

COMPARATIVE WEIGHTS OF ALTERNATING-CURRENT AND ALTERNATING CURRENT-DIRECT CURRENT EQUIPMENTS FOR NEW YORK NEW HAVEN & HARTFORD RAILROAD COMPANY

	Alternating current	Alternating current-direct current
	Pounds	Pounds
4 Motors	31,800	31,800
1 Transformer	7,000	7,000
2 Trolleys with details	1,485	1,485
4 Third rail shoes with fuse boxes		3,200
1 Switch group	1,250	
3 Switch groups		2,700
2 Reversers	400	400
1 Line switch	585	585
1 Set grids	480	1,800
Bus line receptacles and jumpers	75	75
Train line receptacles and jumpers	100	175
2 Master controllers	100	150
Limit switches and line relays	60	80
Battery and charging set	325	325
Pneumatic and insulating details	90	100
Main switch		40
Wattmeter		40
Changeover switch		200
Cables	750	1,500
Blower outfit	800	800
Tablet board and lighting details	450	450
Erection details	1,500	2,500
	47,250	55,405

current equipment. Weight is bad enough, but complication is worse. Great strides have been made in the simplification of the alternating-current-direct-current apparatus, but even with all of this, it is interesting to note the comparison between weights and control for the two classes of equipment. In table 7 herewith, it is to be noted that the straight single-phase equipment is over 8000 lb. lighter than the alternating-current-direct-current equipment, and in the diagram of connections Fig. 42 it is to be noted that the number of unit switches for the alternating-current-direct-current control are 100

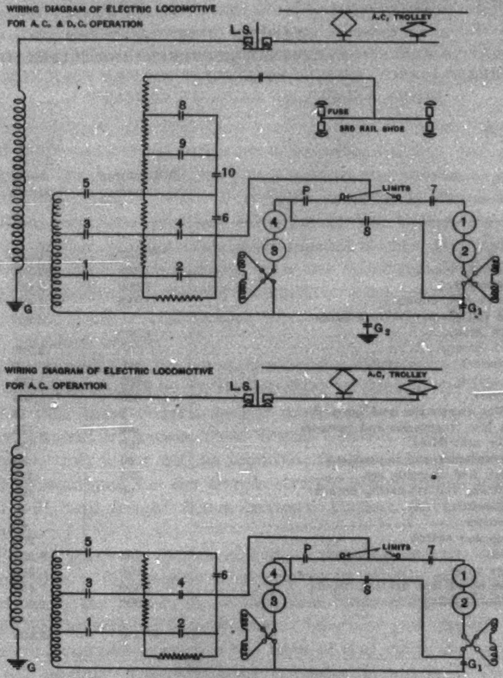

WIRING DIAGRAM OF ELECTRIC LOCOMOTIVE
FOR A.C. & D.C. OPERATION
L.S.
A.C. TROLLEY
FUSE
3RD RAIL SHOE
8
9
10
5
3
4
6
1
2
P
LIMITS
7
4
3
1
2
8
G
G1
G2
WIRING DIAGRAM OF ELECTRIC LOCOMOTIVE
FOR A.C. OPERATION
L.S.
A.C. TROLLEY
5
3
4
6
1
2
P
LIMITS
7
4
3
1
2
8
G
G1

FIG. 42.—Wiring diagram electric locomotives

per cent greater than those of the straight single-phase. To the previous multiple-unit equipment mentioned there will be added (now under construction) four motor cars and twelve trailers. These, unfortunately, again will have to be equipped for interchangeable alternating-current-direct-current operation. The equipments, however, to be ordered in connection with the Harlem River Branch electrification and the New York Westchester & Boston electrification will be free from the intricacies necessary to this dual service, these latter equipments, together with the freight and switching engines, being of the straight single-phase design.

GENERAL CATENARY CONSTRUCTION

In the simultaneous authorization of the electrification of the six-track Harlem River Branch for freight and passenger operation, the New York Westchester & Boston and the Hoosac Tunnel, it naturally made it imperative for the engineers of the New Haven Road to prepare a very extensive set of plans to cover completely these three constructions. Illustrative of the flexibility and adaptability to standardization of the single-phase system, while the Harlem River six-track work required a longer and stronger bridge than the four track New York Westchester & Boston railroad, the general design of both, however, are the same; and notwithstanding the difference in number of tracks, the wire plans for the overhead catenary system of the four-track were applicable to the six-track, the simple addition of two tracks merely meaning an additional 50 per cent increase of material and an equal percentage of weights and stresses for the bridges to sustain.

Space does not permit a lengthy discussion of the general drawings and plans that have been presented in this paper. Owing to the necessary reduction, in reproducing the tracings, the figures on the illustrations and particularly those of the strain and deflection tables, have been reduced to sizes which are difficult to read, without the aid of a glass. However, in including these drawings, my thought was that they would be an epitome of the extensiveness of the work under way, and give some idea of the methods involved in its general specification.

It will be of interest, no doubt, to state that in all the New Haven electrification drawings, it has been the attempt to make each one, while descriptive of the construction desired, at the same time a specification of procedure in erection.

In the case of the New York Westchester & Boston and the Harlem River electrifications we were able to assign to this work Mr. P. J. Kearny and Mr. L. S. Boggs, respectively, who had had previous catenary construction experience with the New Haven, and who were in touch with the methods pursued in its electrification work.

In the case of the Hoosac Tunnel electrification, coming at the same time as the two previous works referred to, and finding ourselves lacking the necessary engineer for this work, Mr. L. B. Stillwell, of New York, was offered and accepted the position as engineer in charge of this work, reporting to the engineering department of the New Haven road, of which Mr. E. H. McHenry is vice-president. As indicated in the prints included in this paper, covering the Hoosac Tunnel catenary construction, it is to be noted that these all bear a similar appearance to those relating to the two other electrifications previously referred to. While the electrification of the tunnel and its approaches is not yet complete, it is rapidly nearing this stage. Electric locomotive operation for instruction of engineers has already started on the North Adams approach of the tunnel in anticipation of regular service.

The Hoosac Tunnel electrification is characteristic for its simplicity. In the case of its power house, two turbo-generators each of 3000 kw. capacity were installed, with a provision for a third generator of similar capacity. The New Haven company was able to utilize the plans as developed for its recently installed Waterbury station, certain adjustments and additions, however, being required to be made to these plans due to difference of location and size of two of the generating units and switching arrangements necessary to the Hoosac Tunnel single-phase conditions. The locomotives have been referred to before; they are characteristic for their simplicity, the cabs being roomy, the control apparatus being centrally arranged and most accessible to inspection.

The power house is located 2.4 miles from the track catenaries, and Fig. 43 shows the general wiring diagram of the complete system. Again space does not permit an extensive description of this electrification. Naturally the most interesting part of it is the tunnel itself. The introduction of 11,000 volts into this tunnel, with the close overhead clearance that the double-track arrangement requires, afforded an interesting problem in the location and placing of insulators which would insure

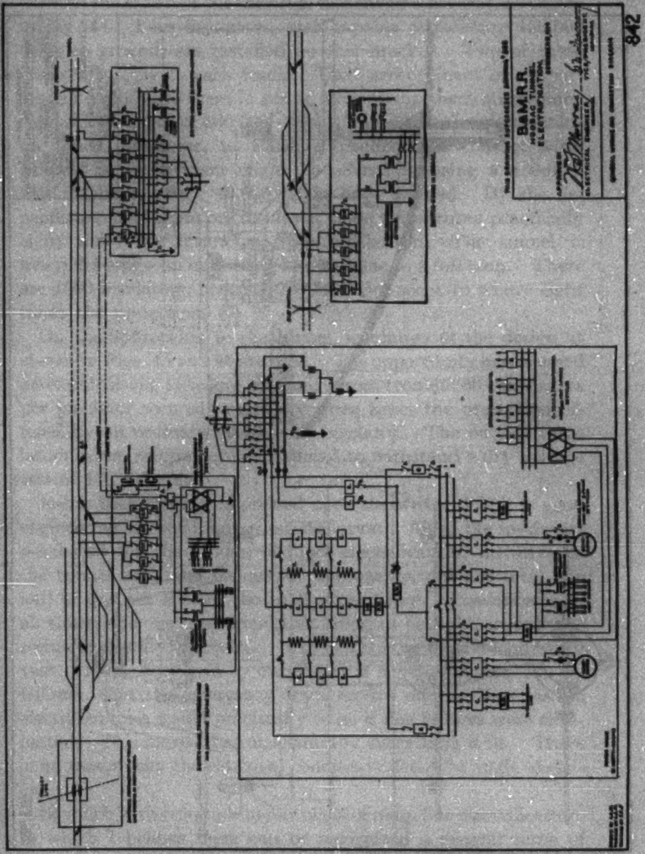

B&M.R.R.
HOOSAC TUNNEL
ELECTRIFICATION
APPROVED
ELECTRICAL ENGINEER
VICE-PRESIDENT
842

Fig. 43.—Hoosac Tunnel general wiring diagram

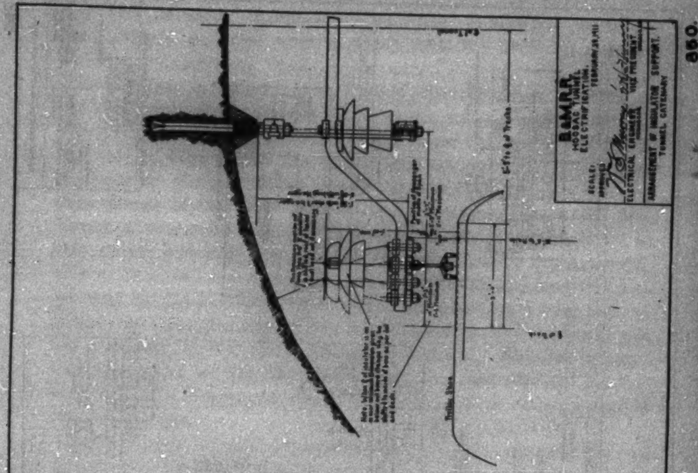

B.&M.R.R.
HOOSAC TUNNEL
ELECTRIFICATION.
SCALE:
APPROVED
ELECTRICAL ENGINEER
VICE PRESIDENT
ARRANGEMENT OF INSULATOR SUPPORT.
TUNNEL CATENARY
850.
SECTION A-A
Trolley Wire
A
A

FIG. 44.—Hoosac Tunnel catenary bracket

against any breakdowns between the electrified wires and ground.

From the crown of the tunnel is suspended a bracket, as shown in Fig. 44. Four insulators, each capable of resisting 150,000 volts to ground, are installed on this bracket. Two of these insulators apply to each track. Their arrangement of support is such as to place them in series, thus giving them a combined dielectric strength of 300,000 volts. The outside insulator holds the track messenger, to which is pendent the contact wires below. Some criticism might be offered in using a 150,000-volt insulator, where 40,000 might have sufficed. By the expenditure of $1 more per insulator, there was secured practically eight times the insurance from breakdown. The tunnel is five miles long—an unhandy place to come to a full stop. There are 1000 insulators; hence $1000 has been spent to secure eight times the protection.

On the approaches to the tunnel, insulators of the design as shown in Figs. 45 and 46 are used. The opportunity here seemed an excellent one to secure immunity from trouble; 50 cents extra per insulator secured practically three times the protection offered by an ordinary 40,000-volt insulator. The outside insulators before erection are all required to withstand a dry voltage test of 110,000 volts.

It has been forcibly impressed upon the writer that it is good engineering to spend money on insulation. All of the insulators purchased for the Hoosac Tunnel electrification, inclusive of the tunnel itself and its outside approaches, did not total one half of one per cent of the total expenditure. *Insulation* is of all things the one most important thing to be right, in order to secure continuity of service. It pays a handsome dividend every year. It has been said by our electrical superintendent, Mr. H. Gilliam, that the emergency train service on the New Haven electrified lines would practically cease if line failures were eliminated. This means that mechanically everything is fit. There is no reason why the electrical condition cannot be made identical.

So much with reference to our plans of main line electrification, in which I believe there can be recognized a general sense of inherent standardization, notwithstanding they refer to three properties with a variety of service and location.

In a previous part of the paper the electric switch engine has been referred to. Figs. 47 and 48 show two great yards on the

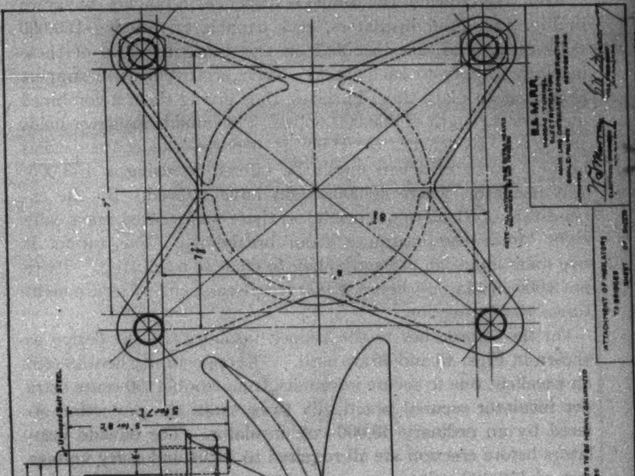

B.& M.R.R.
HOOSAC TUNNEL
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION
ATTACHMENT OF INSULATORS
TO BRIDGES
SHEET OF SHEETS
NOTE ALL METALLIC PARTS TO BE HEAVILY GALVANIZED
BY HOT PROCESS
U-shaped Bolt STEEL
7'
8'
7½"
802

Fig. 45.—B. & M. Main line insulator

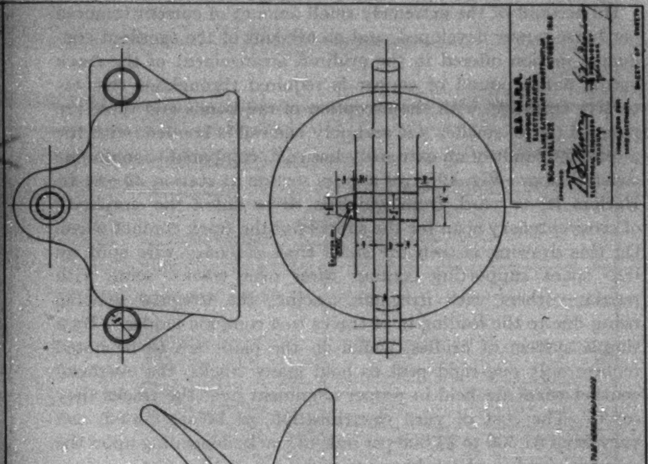

B. & M. R.R.
HOOSAC TUNNEL
ELECTRIFICATION
SCALE FULL SIZE
803

FIG. 46.—Hoosac Tunnel. Insulator for yard catenary

Harlem River branch; one of them covering 20 miles, the other 42.3 miles in tracks that are being electrified, and in which the electric switch engines will work.

On account of the extremely small amount of current required per horse power developed, and on account of the excellent conductor section offered in the gridiron arrangement of the track yards, not a pound of copper is required throughout this extensive trackage, with the exception of rail bonds and these are reduced to the smaller size and only one rail is bonded, with the attendant result of an extremely low cost, compared to main line construction. Fig. 49 gives a cross section at station 22+81 ft. Harlem River yard, from which is to be noted the simplicity of cross catenary span for the support of the track contact wires. On this drawing is seen the same cross catenary wire split up into spans supporting contact wires over tracks, some with regular—others with irregular spacing; the irregular spacing being due to the leading in of tracks to a common ladder. By a simple system of bridles, which on the plans are to be noted require only one rigid post to hold many tracks, the overhead contact wires are held in proper alignment over the tracks they serve. The cost of yard electrification, as before stated, can vary from $1,500 to $3,000 per mile of track, depending upon the average number of tracks spanned.

ELECTRIFICATION COSTS

The question of cost, both with reference to capital investment and operating in connection with electrified lines, is naturally the greatest factor of consideration on the part of railroad companies contemplating the application of electricity to their lines. In this department I am quite in agreement with the previously scorned adage—" Every situation is a study in itself"; for while in my opinion no trunk line electrification can be better served than by the use of single-phase current, it must be conceded that electrification costs must vary with the greatly fluctuating conditions of volume and density of traffic involved. Again, while it would be perfectly possible to state the actual cost involved in handling a train mile by electricity *vs.* a train mile by steam, this information as applying to the New Haven road might be extremely misleading when considered for other application. It is not to present any information not generally known, to say that power houses can be constructed, depending upon the capacity, from $90 to $110 a kilowatt; line construction for

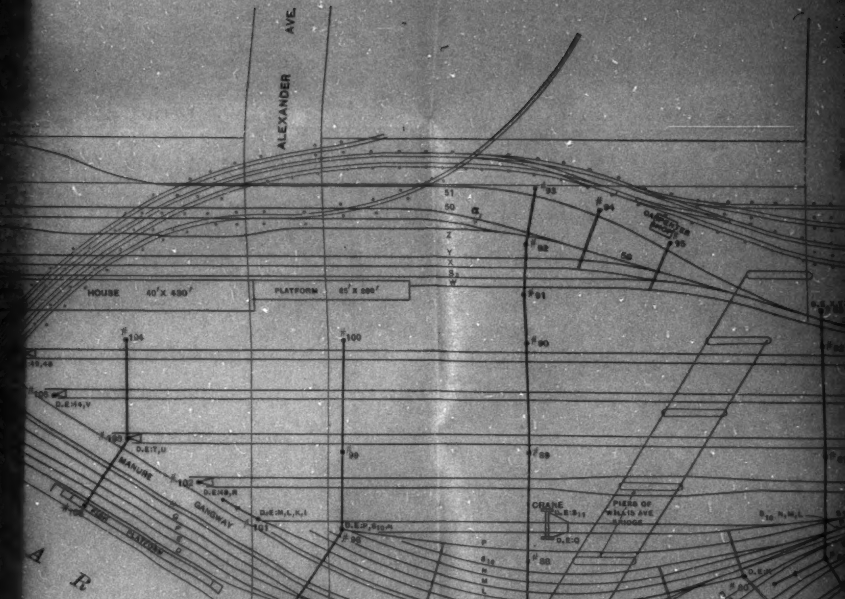
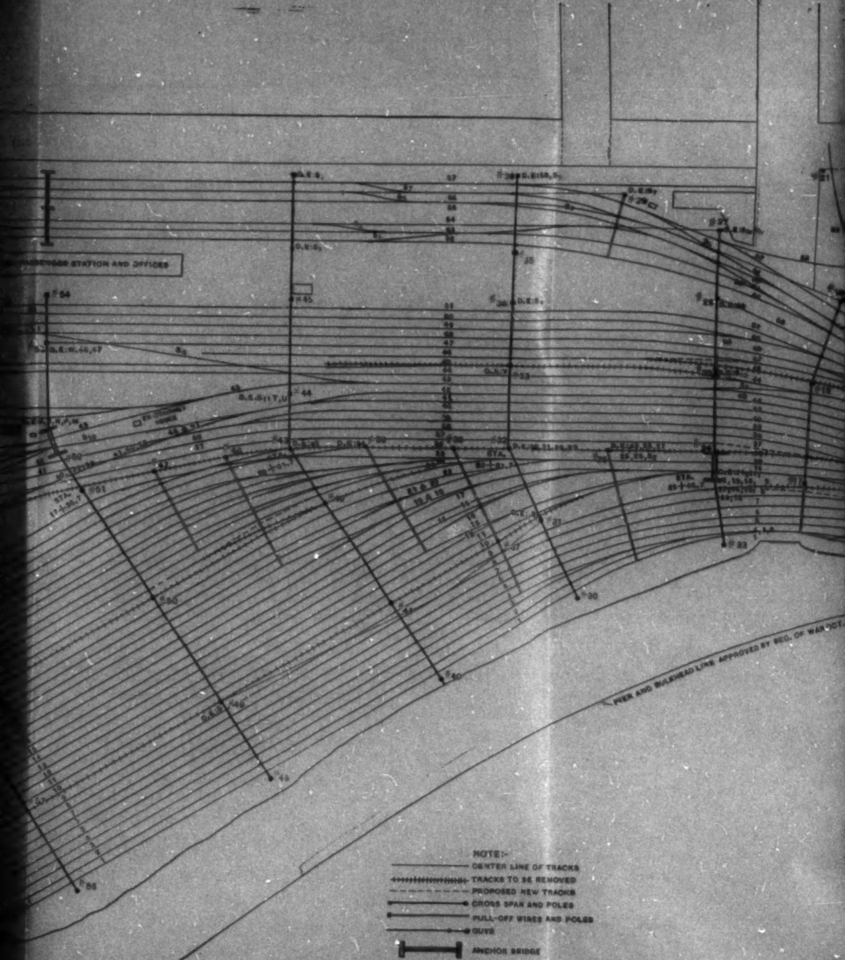
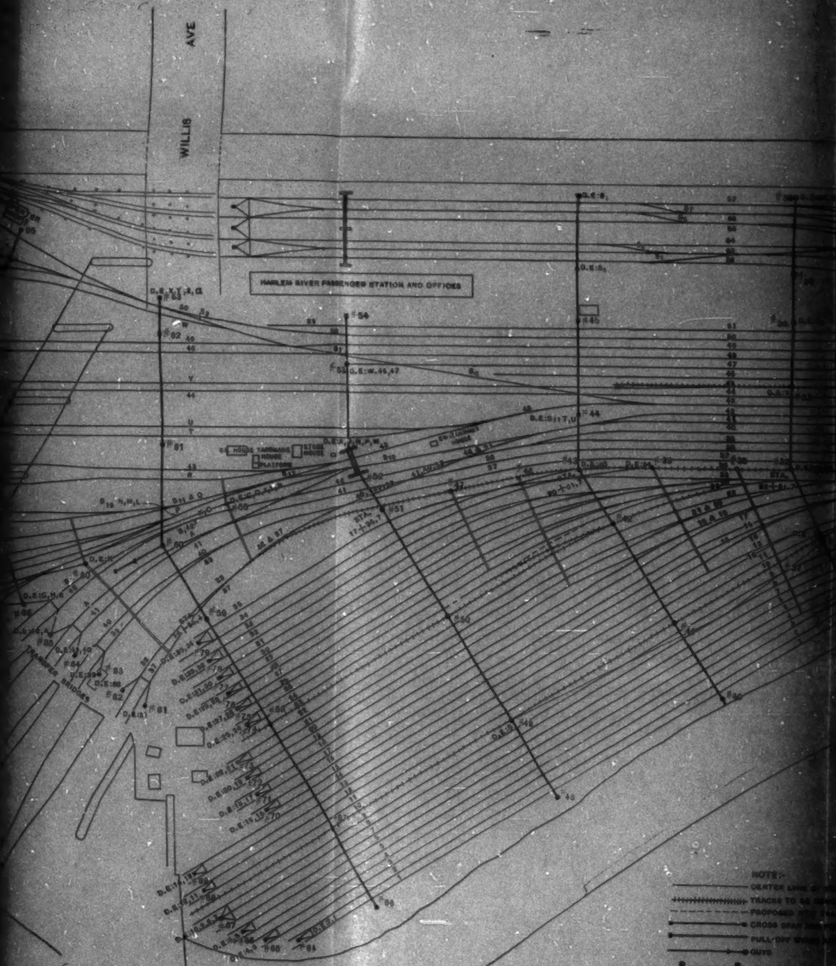

ALEXANDER AVE.
HOUSE 40' X 430'
PLATFORM
51
50
Z
Y
X
W
59
CARPENTER SHOP
CRANE
PIERS OF WILLIS AVE BRIDGE
MANURE GANGWAY
PLATFORM
COAL POCKET
TRANSFER BRIDGES
HARLEM RIVER
PIER AND BULKHEAD LINE APPROVED BY THE SEC. OF WAR OCT. 16, 1900
#106
#105
#104
#103
#102
#101
#100
#99
#98
#97
#96
#95
#94
#93
#92
#91
#90
#89
#88
#87
#86
#85
#84
#83
#82
#81
#80
D.E:T,U
D.E:M,L,K,I
P
H
M
L
K
L
H
G
C

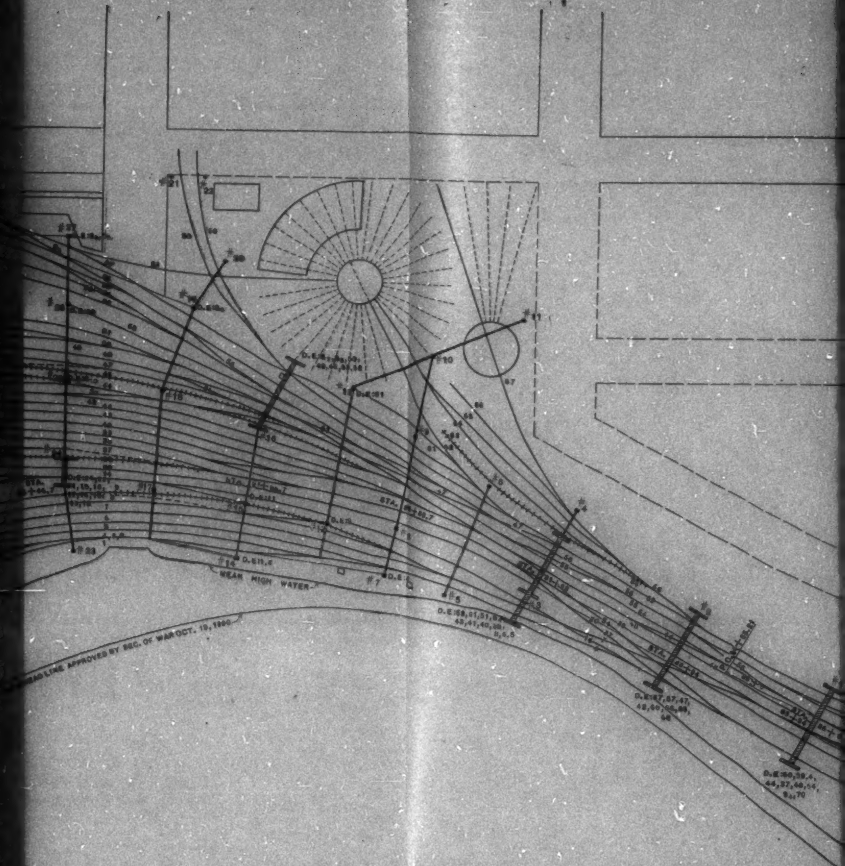
FIG. 47.—Harlem River Yard Layout


STATION AND OFFICES
#54
#53 O.E:W.46,47
O.E:S11 T,U
#44
#45
#43
#42
#41
#40
#39
#38
#37
#36
#35
#34
#33
#32
#31
#30
#29
#28
#27
#26
#24
#23
#17
#16
#21
#52
#51
#50
#49
#48
#47
#46
#56
STA. 17+95.7
STA. 25+66.7
PIER AND BULKHEAD LINE APPROVED BY SEC. OF WAR OCT.
NOTE:-
CENTER LINE OF TRACKS
TRACKS TO BE REMOVED
PROPOSED NEW TRACKS
CROSS SPAN AND POLES
PULL-OFF WIRES AND POLES
GUYS
ANCHOR BRIDGE

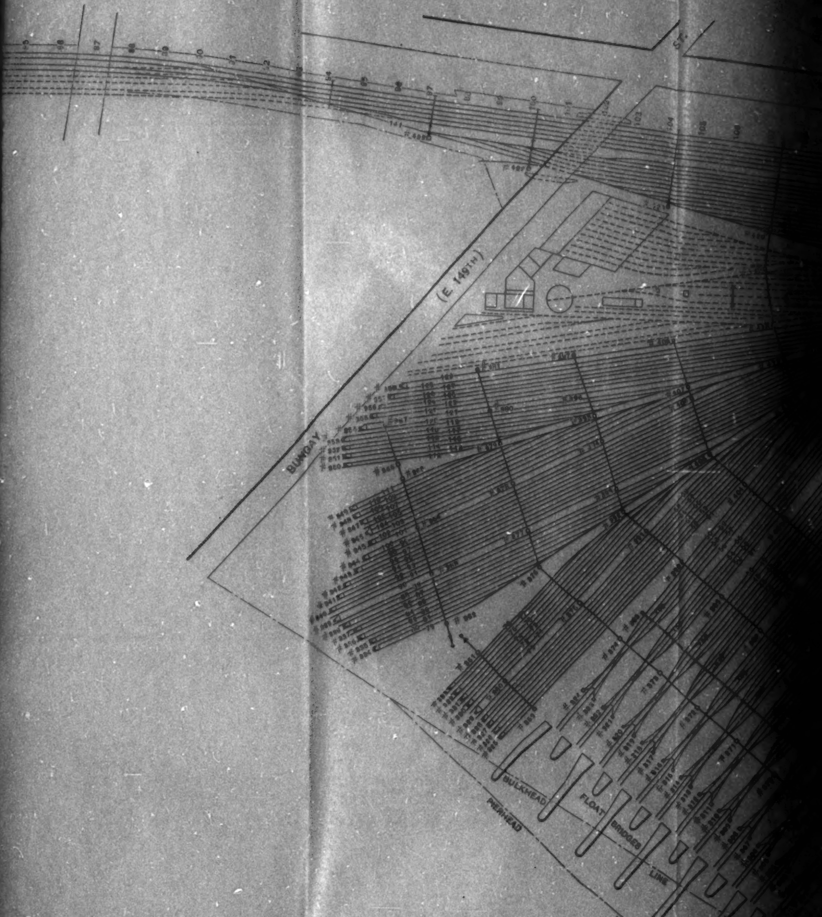
(Murray 14

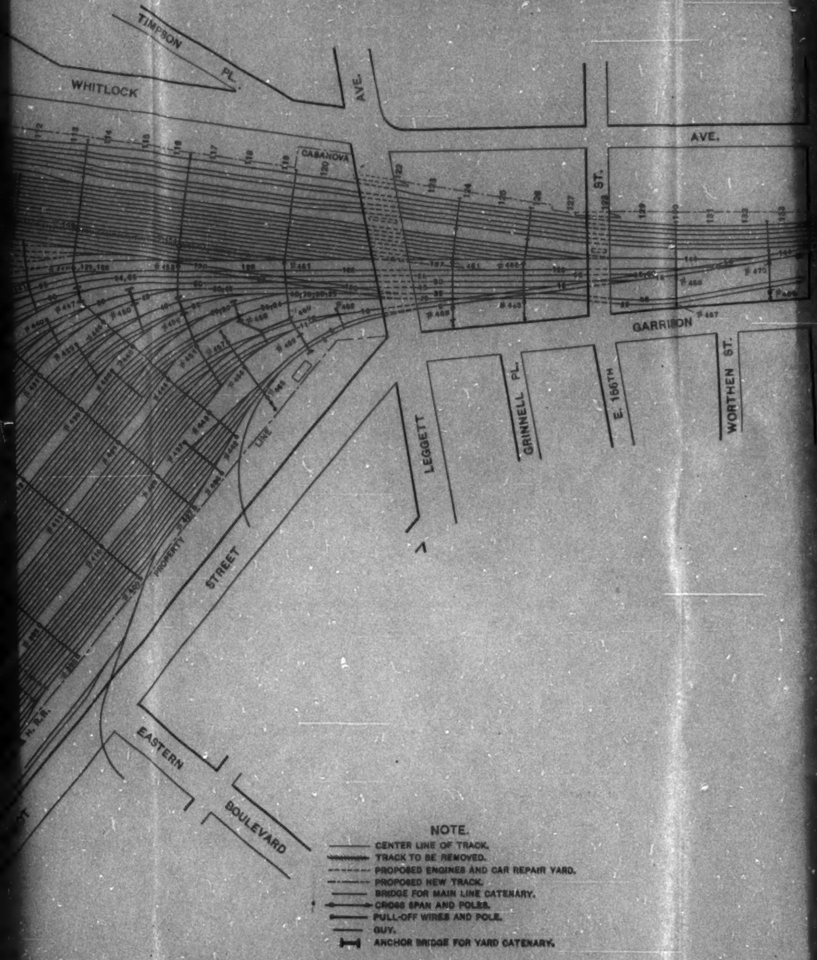

WILLIS
AVE
HARLEM RIVER PASSENGER STATION AND OFFICES
YARDMANS HOUSE
STORE HOUSE
PLATFORM
TRANSFER BRIDGES
NOTE:-
CENTER LINE OF
TRACKS TO BE
PROPOSED NEW
CROSS SPAN
PULL-OFF WIRES
GUYS
ANCHOR BRIDGE
#54
#53
#52
#51
#50
#49
#48
#45
#44
#43
#42
#61
#62
#63
#60
#59
#58
#57
#56
#40
#46
#80
#81
#82
#83
#84
#85
#86
#70
#71
#72
#73
#74
#75
#76
#77
#78
#79

n River Yard Layout


MEAN HIGH WATER
...HEAD LINE APPROVED BY SEC. OF WAR OCT. 19, 1890
#1
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
#13
#14
#15
#16
#17
#18
#19
#20
#21
#22
#23
#27
STA.
D.E.

(Murray 1440)


ST.
BUNGAY
(E. 149TH)
BULKHEAD
FLOAT
BRIDGES
LINE
PIERHEAD
LINE


TIMPSON PL.
WHITLOCK
AVE.
CASANOVA
ST.
AVE.
GARRISON
LEGGETT
GRINNELL PL.
E. 156TH
WORTHEN ST.
PROPERTY LINE
STREET
EASTERN BOULEVARD
H. R.R.
NOTE.
CENTER LINE OF TRACK.
TRACK TO BE REMOVED.
PROPOSED ENGINES AND CAR REPAIR YARD.
PROPOSED NEW TRACK.
BRIDGE FOR MAIN LINE CATENARY.
CROSS SPAN AND POLES.
PULL-OFF WIRES AND POLE.
GUY.
ANCHOR BRIDGE FOR YARD CATENARY.

48.—Oak Point Yard Plan

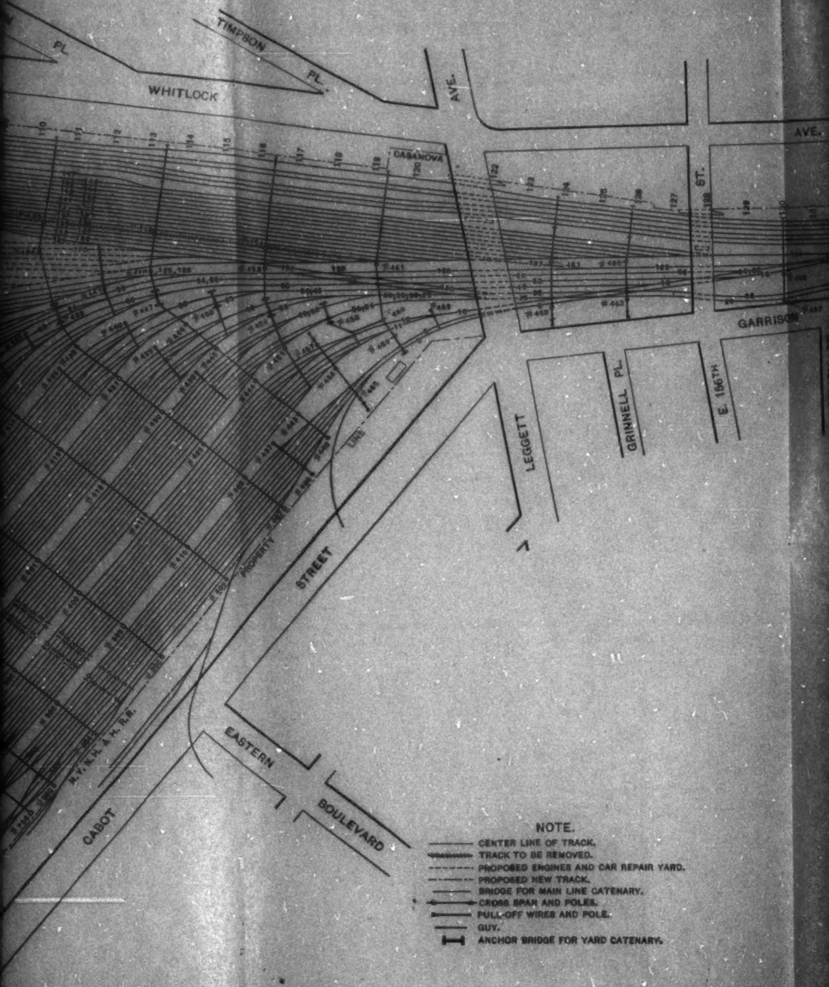
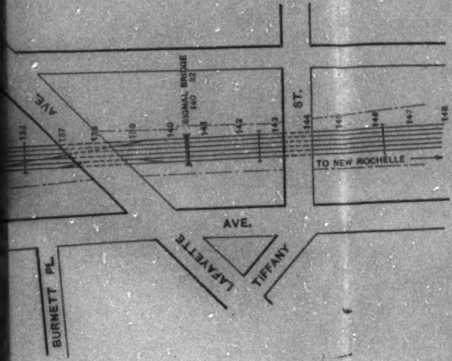

WHITLOCK
TIMPSON
PL.
PL.
AVE.
AVE.
CASANOVA
ST.
GARRISON
LEGGETT
GRINNELL PL.
E. 156TH
PROPERTY
LINE
STREET
EASTERN
BOULEVARD
CABOT
N.Y., N.H. & H. R.R.
NOTE.
CENTER LINE OF TRACK.
TRACK TO BE REMOVED.
PROPOSED ENGINES AND CAR REPAIR YARD.
PROPOSED NEW TRACK.
BRIDGE FOR MAIN LINE CATENARY.
CROSS SPAN AND POLES.
PULL-OFF WIRES AND POLE.
GUY.
ANCHOR BRIDGE FOR YARD CATENARY.

Fig. 48.—Oak Point Yard Plan


AVE
133
137
138
139
140
SIGNAL BRIDGE
140 32
141
142
143
ST.
144
145
146
147
148
TO NEW ROCHELLE
AVE.
LAFAYETTE
TIFFANY
BURNETT PL.

Track No.	East dead end at bridge or post No.	West dead end at bridge or post No.	Track No.
1	459	302	41
2	459	301/302	42
3	459	301/302	43
4	459	302	44
5	463	301	45
6	468	304	46
7	459	303	47
8	459	303/304	48
9	459	303/304	49
10	459	303	50
11	Legget Av. Br'ge.	306	51
12	460	305/306	52
13	460	305/306	53
14	460	306	54
15	462	305	55
16	Longwood Av. Br.	308	56
17	460	307	57
18	460	307/308	58
19	460	307/308	59
20	462	307	60
21	458	310	61
22	458	309/310	62
23	458	309/310	63
24	Legget Av. Br'ge.	310	64
25	Longwood Av. Br.	309	65
26	458	312	66
27	458	311	67
28	458	311/312	68
29	Legget Ave. Br'ge.	311/312	69
30	Legget Av. Br'ge.	311	70
31	452	314	71
32	452	313/314	72
33	452	313/314	73
34	458	314	74
35	Longwood Av. Br'ge.	313	75
36	452	316	76
37	452	315	77
38	452	315/316	78
39	452	315/316	79
40	Legget Av. Br'ge.	315	80

(Murray 1440a.)

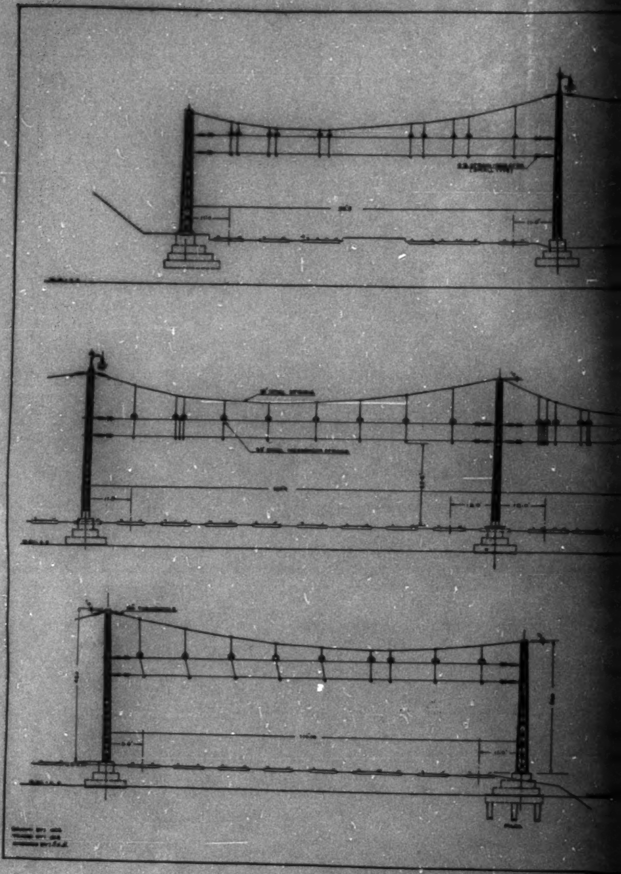
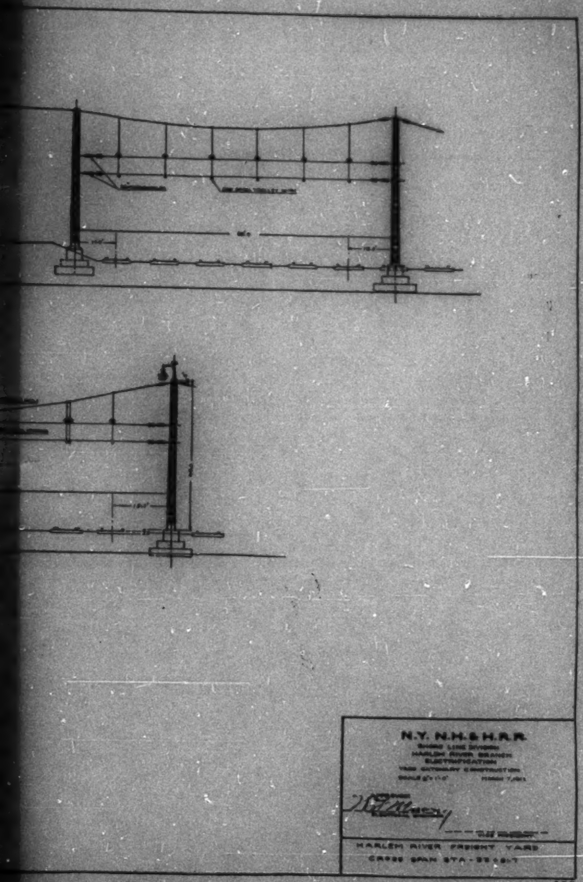


Fig. 49.—Harlem River Branch cro


N.Y. N.H.& H.R.R.
SHORE LINE DIVISION
HARLEM RIVER BRANCH
ELECTRIFICATION
YARD CATENARY CONSTRUCTION
VICE PRESIDENT
HARLEM RIVER FREIGHT YARD
CROSS SPAN STA.-33+81.7

bridges and foundations

(Murray 1440b.)

one, two, four and six tracks can be erected at costs varying respectively from $4,000 to $7,000; from $8,000 to $15,000; from $25,000 to $40,000; $40,000 to $60,000 a mile; the fluctuation in cost for these respective constructions depending entirely upon the standards elected, which are inclusive of the consideration of importance of track, in turn bringing into consideration the advisability of wood and steel post construction, cross catenary and bridge span construction, single or compound catenaries, etc., also the cost of overhead yard construction can vary from $1,500 to $3,000 a mile, depending upon number of tracks spanned and type of construction selected.

Locomotives of the passenger road and switching type, depending upon the nature of their service, can vary in cost from $25,000 to $45,000 a unit. Thus it is seen that it would be impossible, from the capital point of view, to give a useable estimate of electrification cost. Again the necessity of property acquisitions, which in one case may be nothing and in another a very large sum, all varying in accordance with the environment of the electrification in question, make such studies individual to the specific cases under consideration.

In general, from an electrical operating standpoint, it may be stated that for trunk line properties, where a very considerable density of traffic is involved, there will be shown a considerable debit in the department of "maintenance of way and structures," while in the departments of "maintenance of equipment and transportation expenses" a large credit, if the proper system is selected, may accrue. The balance between the debit and credit columns furnishes the ground upon which it may be said it is either a good or bad investment for the railroad company to electrify; and yet even though the direct returns prove unsatisfactory, it does not follow that the investment is a bad one if considered from a broader standpoint of general policy.

A most careful analysis of the relation between steam and electricity was made in connection with the lines of the New Haven road west of New Haven. I have no authority, in presenting such a paper as this, to state whether the policy of the railroad company in electrifying over 300 miles of its trunk line rails, terminals and yards was for financial gain to itself or better service to its patrons; but at least it is reasonable to assume that with an application of electricity to cover complete passenger and freight train propulsion and yard switching over the mileage above named, expending millions of dollars to effect such a service, its Directors could not have ratified the extension of the adopted system and its application over such a wide territory in all classes of service, unless the successful and uncompetitive characteristics of the system were not immediately apparent.

Not until the electrical system of the New Haven road is a unit in itself, rather than a mixed service of steam and electricity, can its true economies of electrical traction be discussed. Suffice it to say that the two great departments of economy lie in the saving of fuel and repairs to rolling equipment.

I regret that my contribution in this paper to the many times repeated question as to the cost of electrification cannot bring a definite reply to each request. The electrification of railroads will not await the reply of an impossible inquiry. The practical answer, and substitute for this inquiry, is: As electrification of trunk lines is now practically at hand, what is the correct system for all? Our experience with the single-phase system as applied to the New Haven Road to over 300 miles of its track, with the necessary extension to follow to New Haven, adding 150 more—making a total system, with yards, of nearly 500 miles, may offer a strong suggestion in this direction.

Recommendations. As in the early days when alternating-current application forced its way into the acceptance by its very opposers, so has the force of its application to the trunk line railroad problem impressed the writer that he has not felt it necessary to make any plea for its acceptance. When railroads consider trunk line electrification, all important will be the matter of freight movement and with it the cost and convenience of operation of their yards. The ratio of the mileage of yards in the division run between Harlem River and New Haven to the main line tracks, is over 55 per cent; and while the New Haven road may be considered to have a high ratio of yard mileage to main line mileage, this condition is ever true throughout the railroads of the Atlantic Coast territory. In fact, such a condition is naturally true of any territory including cities and towns of close proximity to each other. In writing this paper, it has been my effort to avoid a discrimination between systems. I wish, however, to state very plainly that I am not at all in sympathy with the attitude on the part of some who claim some recognition in the field of railroad engineering, when they suggest the advisability of not advocating any particular system of electrification. To discuss electricity *vs.* steam without a recommendation of system in the specific cases of trunk line work, in my judgment, is to launch a ship upon a rough and windy sea without a rudder. I plead guilty to a considerable effort in trying to lay before the Institute the facts presented in this paper. I have endeavored to deal with nouns and not adjectives. An extremely important matter would be omitted if I did not say that my experience with the single-phase system *vs.* other competitive systems, affords me the sincere conviction that, under practically all conditions of trunk line consideration where the traffic is of the same amount and character, or indeed much less than that which is comprehended in the mileage that this paper covers, its first cost is at the greatest not more than 85 per cent of its next best competitor, and its operating costs less than the above percentage.

The above statements should not be taken to mean that all trunk line railroads, considering electrification, can electrify and save money; indeed its general application is prohibitive. There are, however, roads that must and will electrify. To such railroads it is my hope that the information compiled will be of value.

It has been suggested by some not altogether friendly even now to the single-phase system, that if this paper be made inclusive of specific recommendations as to system to be applied for trunk line properties, inclusive of suburban and terminal territory, that it might confuse the mind of the railroad man, due to diversity of opinion among electrical engineers on this subject. I wish to say, with reference to this matter, that my opinion of and respect for the railroad man, born of the past six years of intimate association with him, be he an executive of finance, transportation, operation or engineering, is that he is not of the caliber to be confused by a discussion of this subject. I have invariably found rudders on their ships; why not one to ours? And let me assure those who are contrary to this opinion that railroad men can intelligently analyze any argument that is to be advanced—pro or con—on this highly necessary and near decision. The paper, however, is not presented to precipitate an argument; nor is it an argument for the single-phase system. Statistical records of the first cost and operating expense make such a course unnecessary. It has been written with the purpose of placing in the hands of those interested in the electrification of railroads the facts concerning the application of single-phase current to nearly 500 miles of trunk line property and to make a specific recommendation that for the sake of simplicity and economy it be the adopted system for other trunk line properties which the future will see electrified.

I wish to here acknowledge the able services of Mr. Paul Real, my principal assistant, in connection with the preparation of this paper.

APPENDIX

The following illustrations (Figs. 50 to 76) include the detailed drawings pertaining to the overhead catenary construction for:

1. New York, New Haven & Hartford Harlem River Branch.
2. New York Westchester & Boston Railroad.
3. Hoosac Tunnel Electrification.

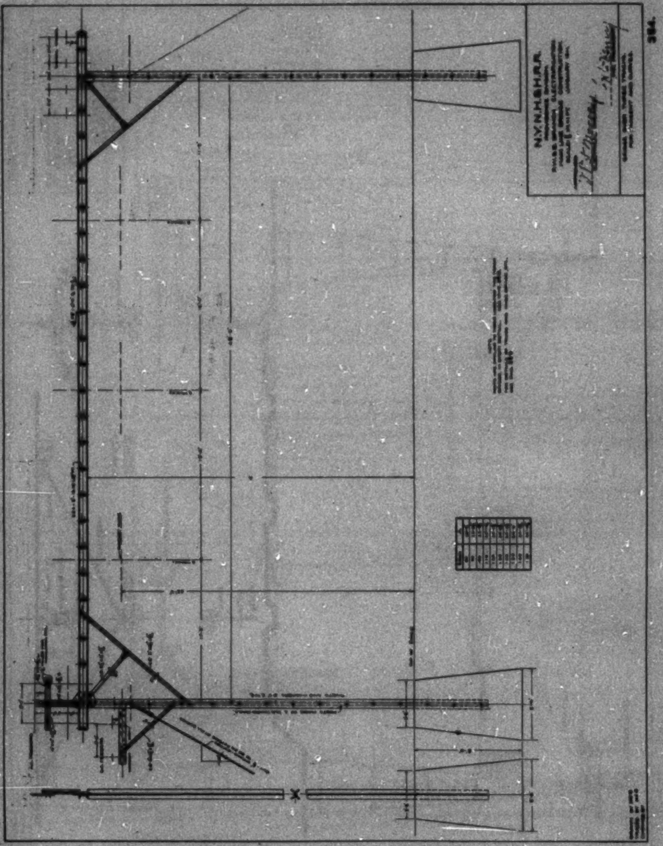

N.Y.N.H.&H.R.R.
384.

FIG. 50.—P. W. & B. branch three-track bridges

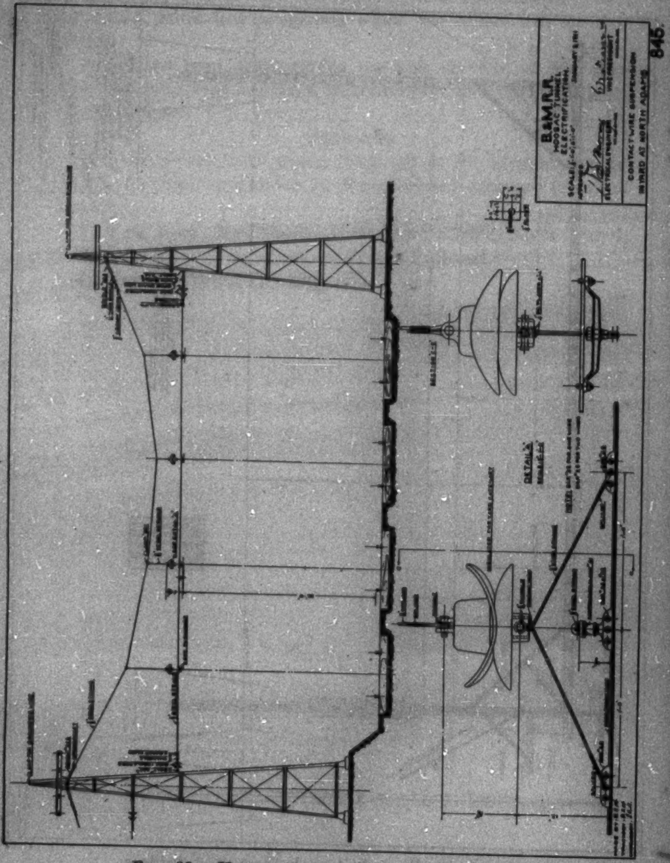

B.&M.R.R.
HOOSAC TUNNEL
ELECTRIFICATION
CONTACT WIRE SUSPENSION
IN YARD AT NORTH ADAMS
845
DETAIL "A"

FIG. 66—Hoosac Tunnel yard construction

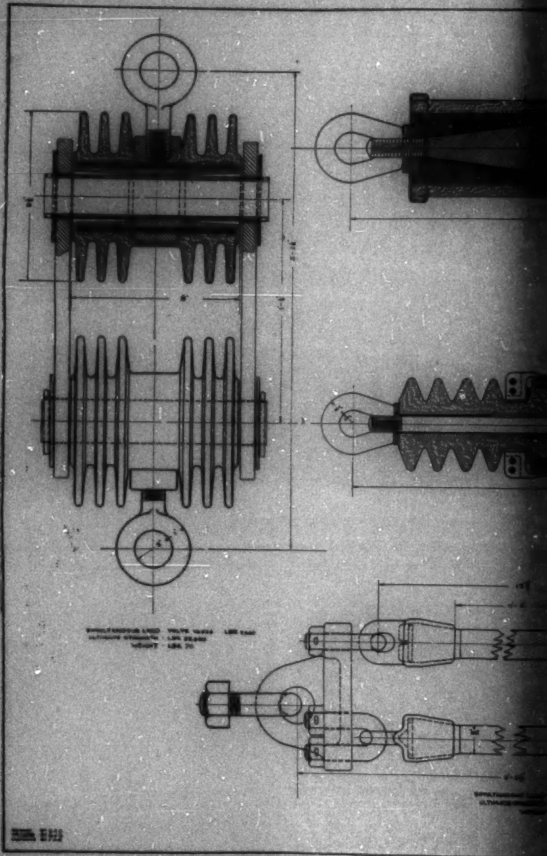
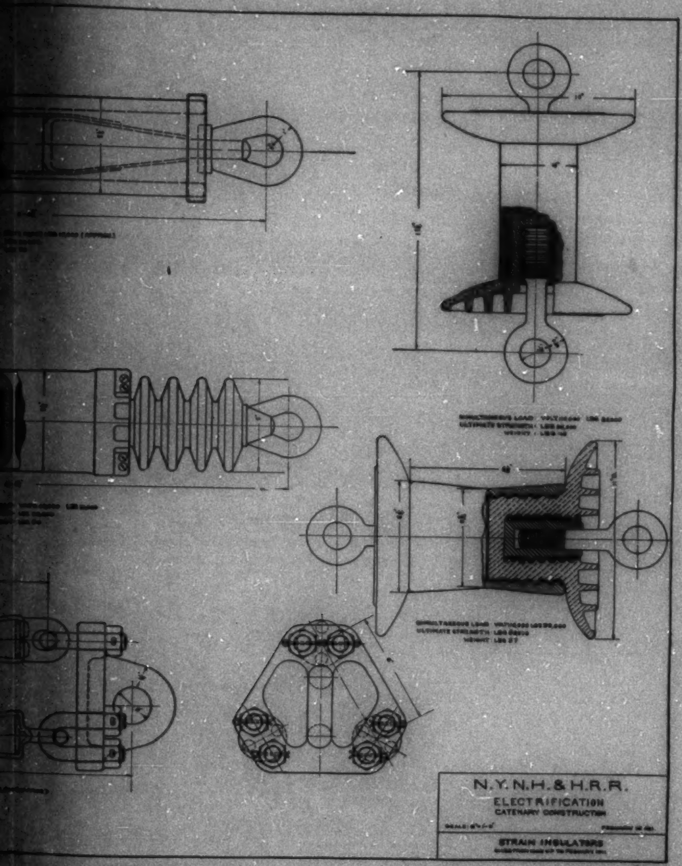


FIG. 51.—N


N.Y.N.H.&H.R.R.
ELECTRIFICATION
CATENARY CONSTRUCTION
STRAIN INSULATORS

52.

& H. strain insulators

(Murray 1446a.)

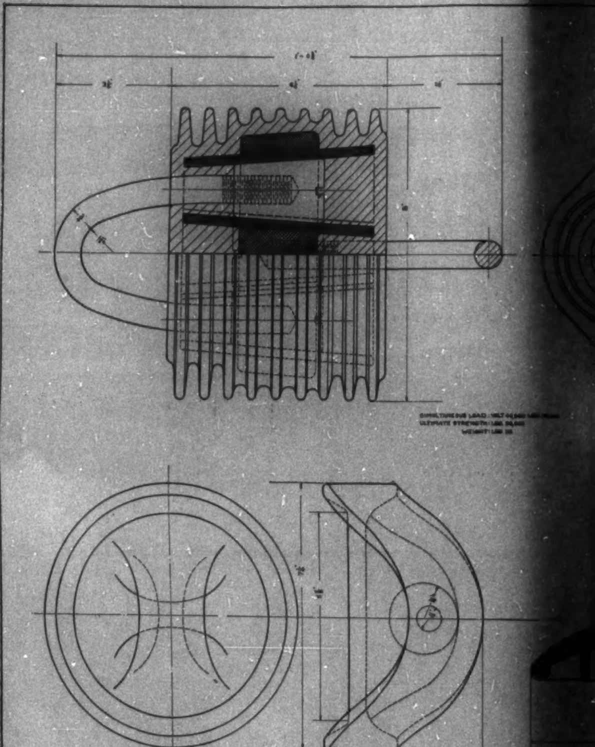
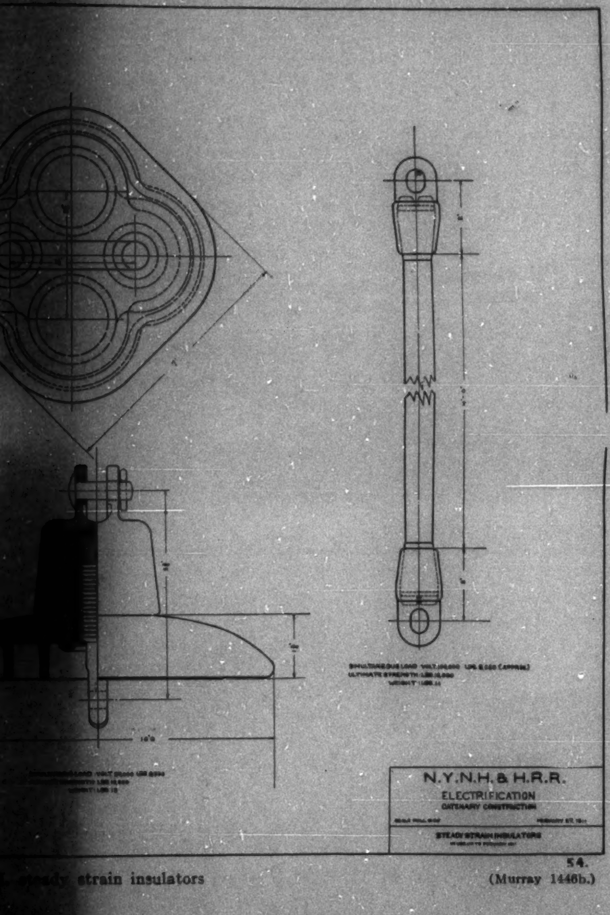

SIMULTANEOUS LOAD
ULTIMATE STRENGTH
WEIGHT
SIMULTANEOUS LOAD
ULTIMATE STRENGTH
WEIGHT

Fig. 52.—N. Y. N. H.


10'6"
N.Y.N.H.& H.R.R.
ELECTRIFICATION
CATENARY CONSTRUCTION
STEADY STRAIN INSULATORS

steady strain insulators

54.
(Murray 1446b.)

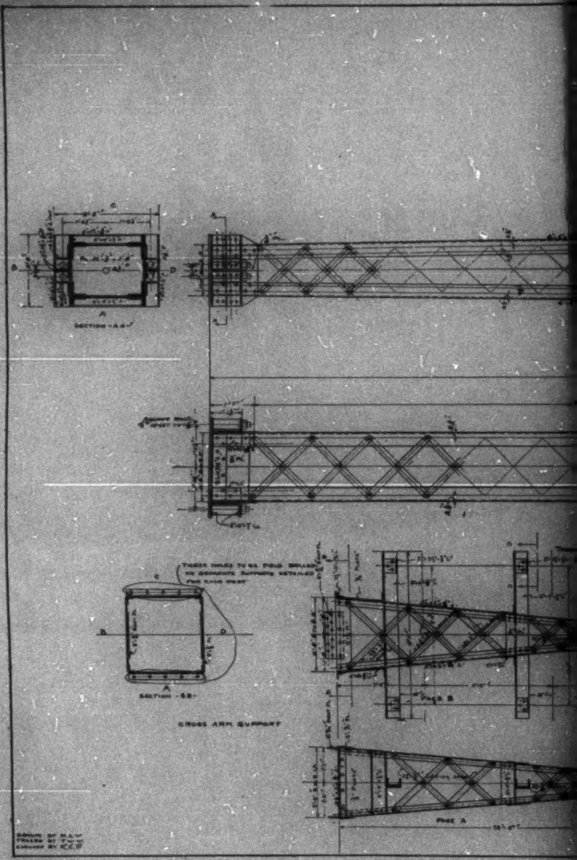
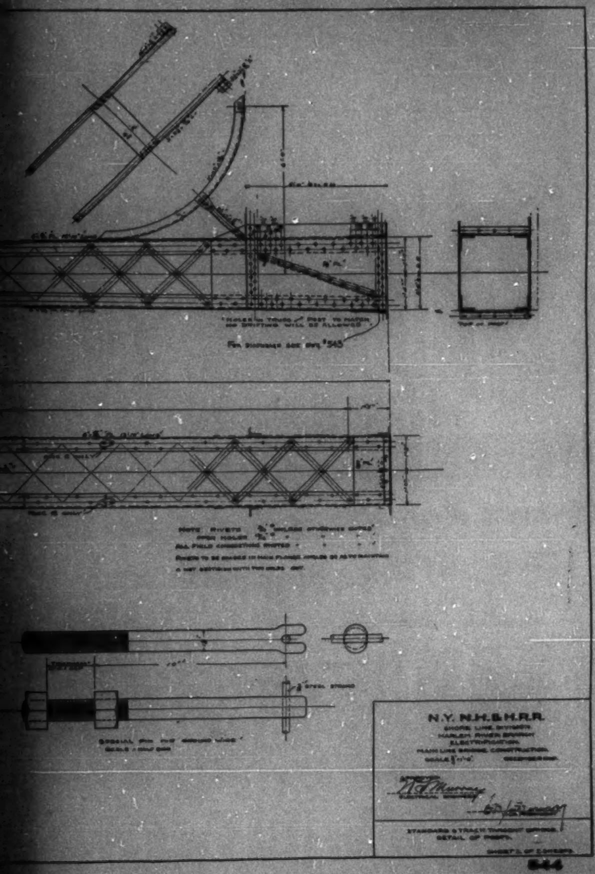

SECTION -AA-
THESE HOLES TO BE FIELD DRILLED OR SEPARATE SUPPORTS DETAILED FOR EACH POST
SECTION -BB-
CROSS ARM SUPPORT
FACE A
FACE B

FIG. 53.—N. Y. N.


HOLES IN TRUSS ... POST TO MATCH, NO DRIFTING WILL BE ALLOWED
For Drawings see Dwg. #543
NOTE: RIVETS ... UNLESS OTHERWISE NOTED
ALL FIELD CONNECTIONS RIVETED
STEEL STRAND
SPECIAL PIN FOR GROUND WIRE
SCALE - HALF SIZE
N.Y. N.H.&H.R.R.
SHORE LINE DIVISION
HARLEM RIVER BRANCH
ELECTRIFICATION
MAIN LINE BRIDGE CONSTRUCTION
W. S. Murray
ELECTRICAL ENGINEER
STANDARD 6 TRACK TANGENT BRIDGE
DETAIL OF POSTS
544

d 6-track tangent post (Murray 1446c.)

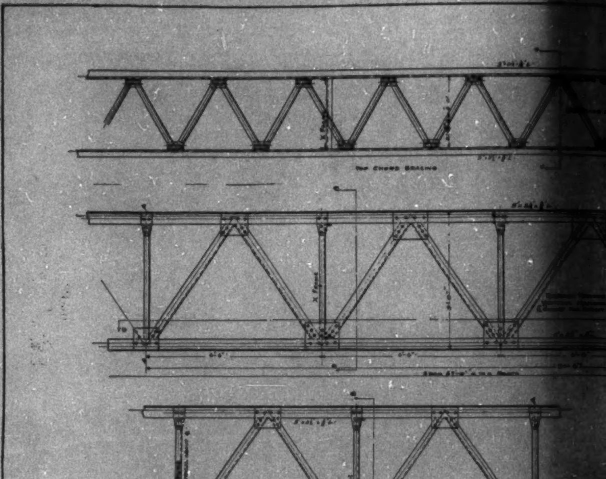
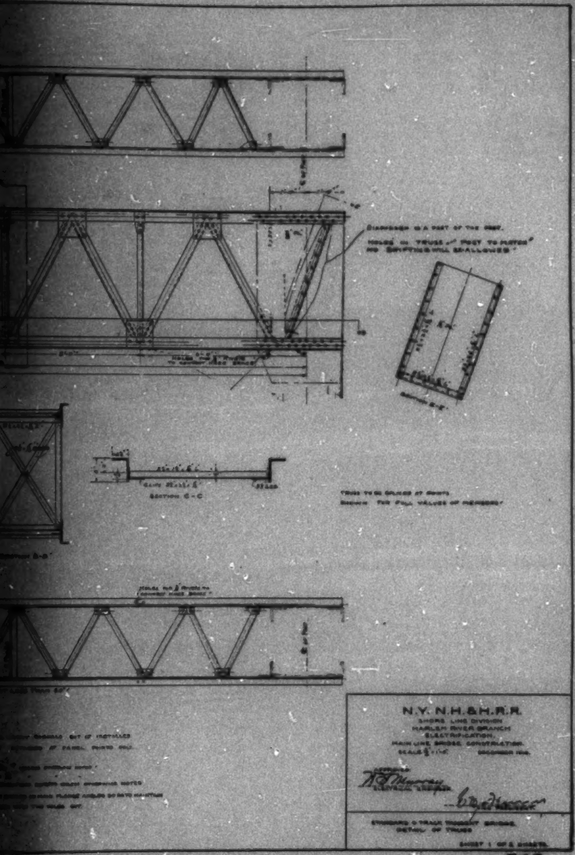

TOP CHORD BRACING
X FRAME
SIDE ELEVATION
SPLICE
SPLICE
DRAWN BY
TRACED BY
CHECKED BY

FIG. 54.—N. Y. N.


Diaphragm is a part of the post.
Holes in truss and post to match. No drifting will be allowed.
Section E-E
Section C-C
Section B-B
Truss to be spliced at points shown. The full values of members.
N.Y. N.H. & H.R.R.
Shore Line Division
Harlem River Branch
Electrification.
Main Line Bridge Construction.
Approved
W. S. Murray
Electrical Engineer
Standard 6-track tangent bridge.
Detail of truss
Sheet 1 of 2 sheets.

843

ard 6-track tangent bridge

(Murray 1446d.)

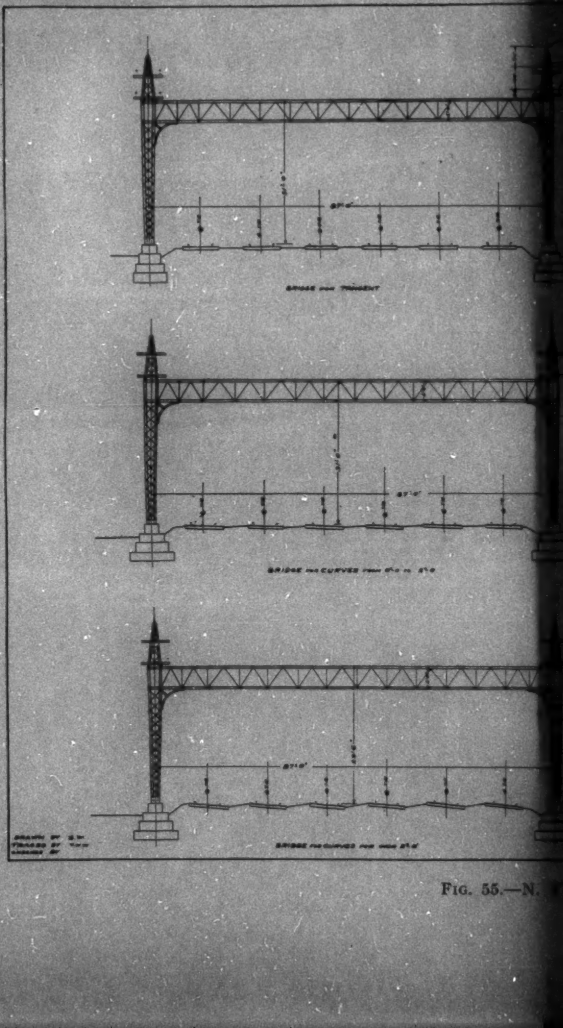
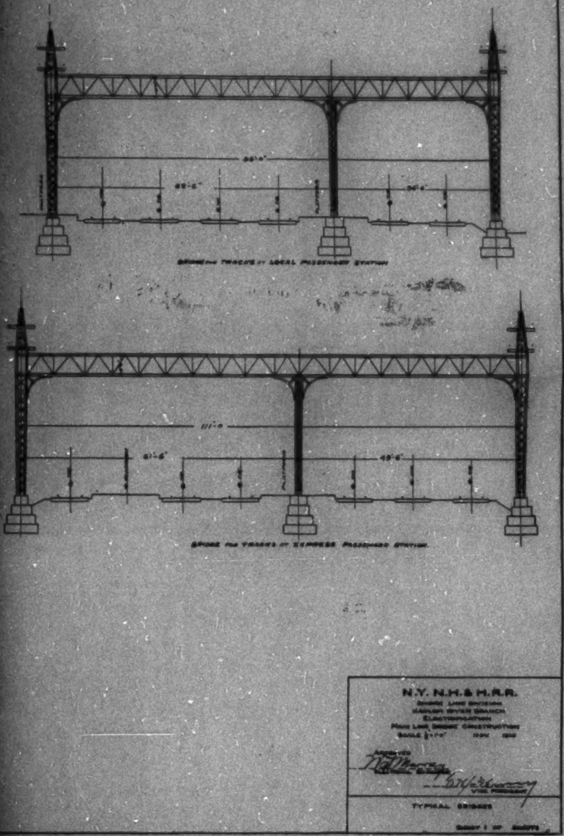

87'-0"
TANGENT
BRIDGE FOR CURVES FROM
87'-0"
87'-0"
BRIDGE FOR CURVES
DRAWN BY
TRACED BY
CHECKED BY

FIG. 55.—N.


86'-0"
63'-6"
34'-6"
BRIDGE FOR TRACKS AT LOCAL PASSENGER STATION
111'-0"
61'-6"
49'-6"
BRIDGE FOR TRACKS AT EXPRESS PASSENGER STATION
N.Y. N.H. & H.R.R.
SHORE LINE DIVISION
HARLEM RIVER BRANCH
ELECTRIFICATION
MAIN LINE BRIDGE CONSTRUCTION
SCALE 1/8"=1'0" NOV 1910
APPROVED
ELECTRICAL ENGINEER
VICE PRESIDENT
TYPICAL BRIDGES
SHEET 1 OF SHEETS

527

H. & H. typical bridges (Murray 1446e.)

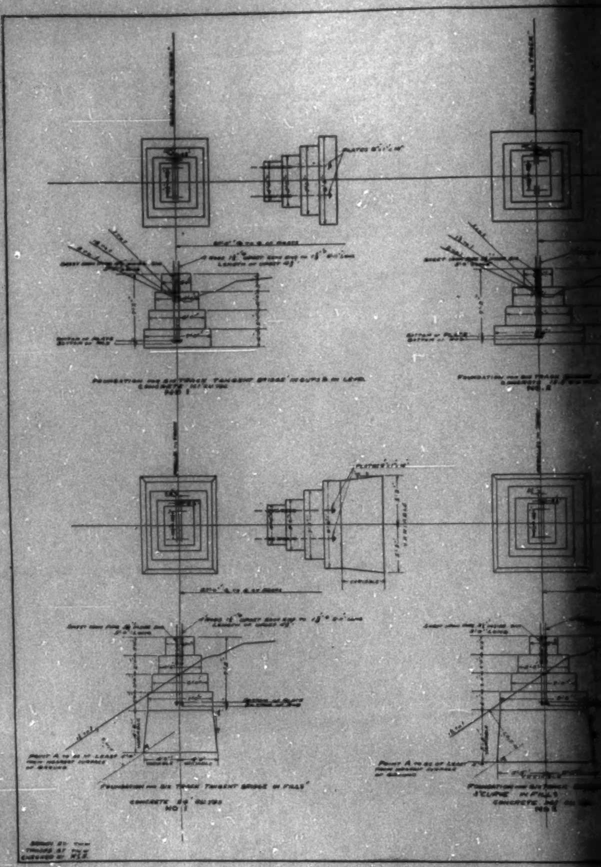
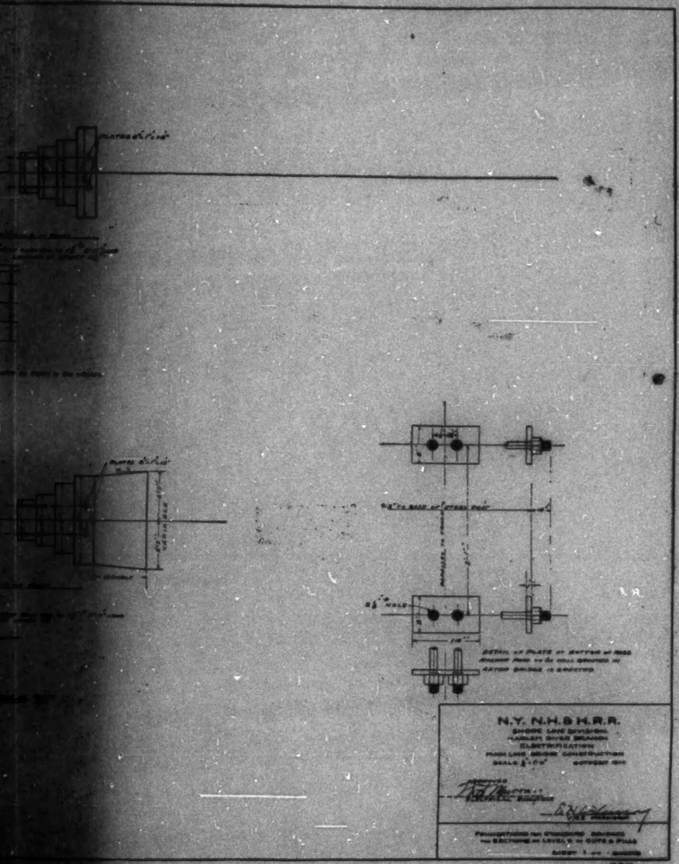

FOUNDATION FOR SIX TRACK TANGENT BRIDGE IN CUTS & ON LEVEL
NO 1
POINT A TO BE AT LEAST
FOUNDATION FOR SIX TRACK TANGENT BRIDGE IN FILLS
CONCRETE 54 CU YDS
NO 1

FIG. 56.—N. Y. N. H.


DETAIL OF PLATE AT BOTTOM OF MASS
ANCHOR ROD TO BE WELL GROUTED IN
AFTER BRIDGE IS ERECTED
N.Y. N.H. & H.R.R.
SHORE LINE DIVISION
HARLEM RIVER BRANCH
ELECTRIFICATION
MAIN LINE BRIDGE CONSTRUCTION
OCTOBER 1910
APPROVED
ELECTRICAL ENGINEER
FOUNDATIONS FOR STANDARD BRIDGES
FOR SECTIONS AT LEVELS IN CUTS & FILLS
SHEET 1 OF SHEETS
585

Foundation plans (Murray 1446f.)

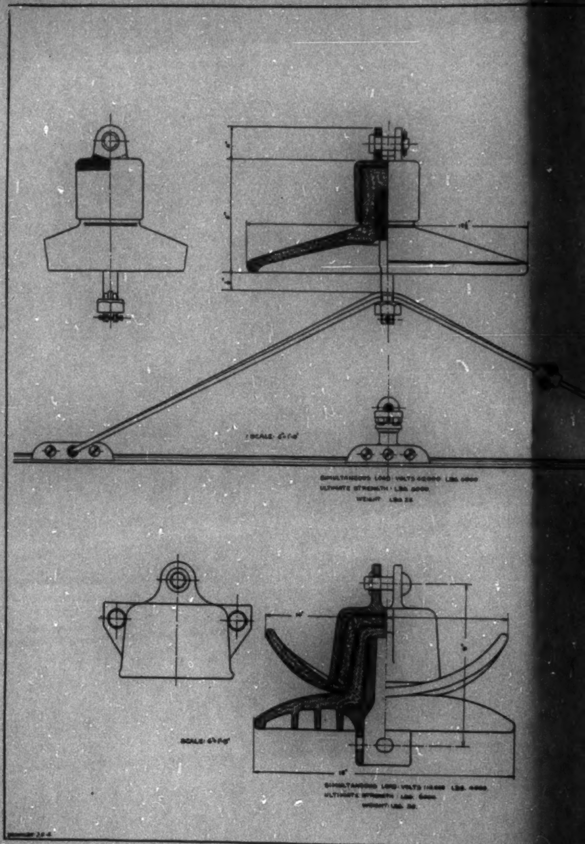
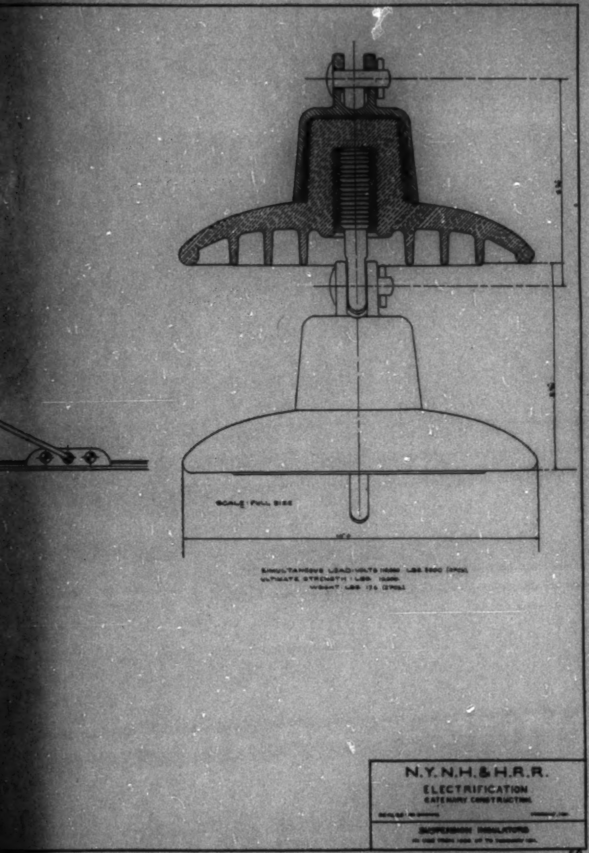

SCALE
SIMULTANEOUS LOAD: VOLTS
ULTIMATE STRENGTH: LBS.
WEIGHT: LBS.
SCALE
SIMULTANEOUS LOAD: VOLTS
ULTIMATE STRENGTH: LBS.
WEIGHT: LBS.

FIG. 57.—


SCALE: FULL SIZE
SIMULTANEOUS LOAD: VOLTS [illegible] LBS. [illegible]
ULTIMATE STRENGTH: LBS. [illegible]
WEIGHT: LBS. [illegible]
N.Y.N.H.&H.R.R.
ELECTRIFICATION
CATENARY CONSTRUCTION
SUSPENSION INSULATORS

58.

Insulators

(Murray 1446g.)

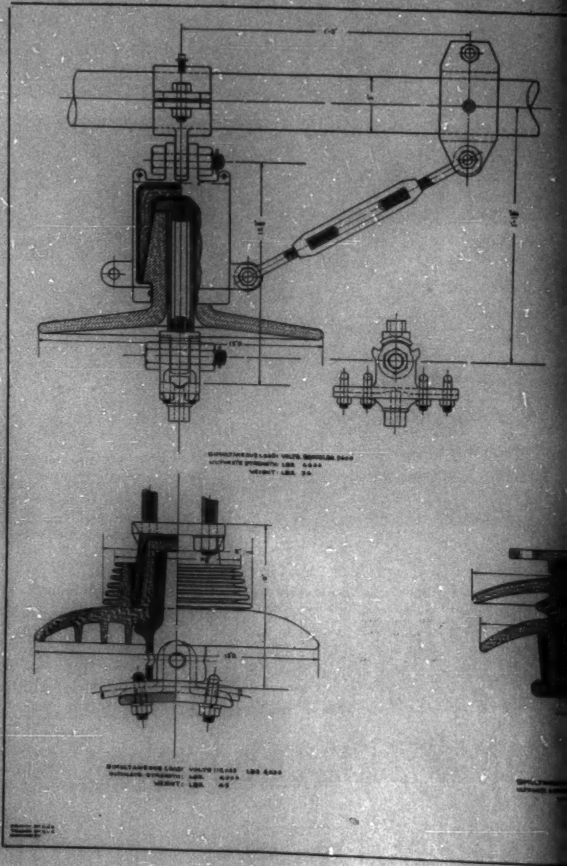
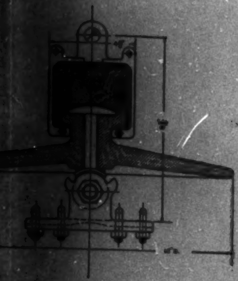
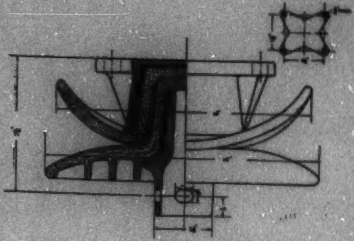

1'-0"
SIMULTANEOUS LOAD: VOLTS
ULTIMATE STRENGTH: LBS.
WEIGHT: LBS.
SIMULTANEOUS LOAD: VOLTS
ULTIMATE STRENGTH: LBS.
WEIGHT: LBS.

FIG. 58.—



[illegible] LOAD: VOLT [illegible] LBS [illegible]
[illegible] STRENGTH: LBS. [illegible]
WEIGHT: LBS. [illegible]



SIMULTANEOUS LOAD: VOLT [illegible] LBS [illegible]
ULTIMATE STRENGTH: LBS. [illegible]
WEIGHT: LBS. [illegible]

N Y N.H. & H.R.R.
ELECTRIFICATION
CATENARY CONSTRUCTION
[illegible] [illegible]

SUSPENSION INSULATOR FOR MAIN LINE
[illegible]

insulators

60.

(Murray 1446h.)

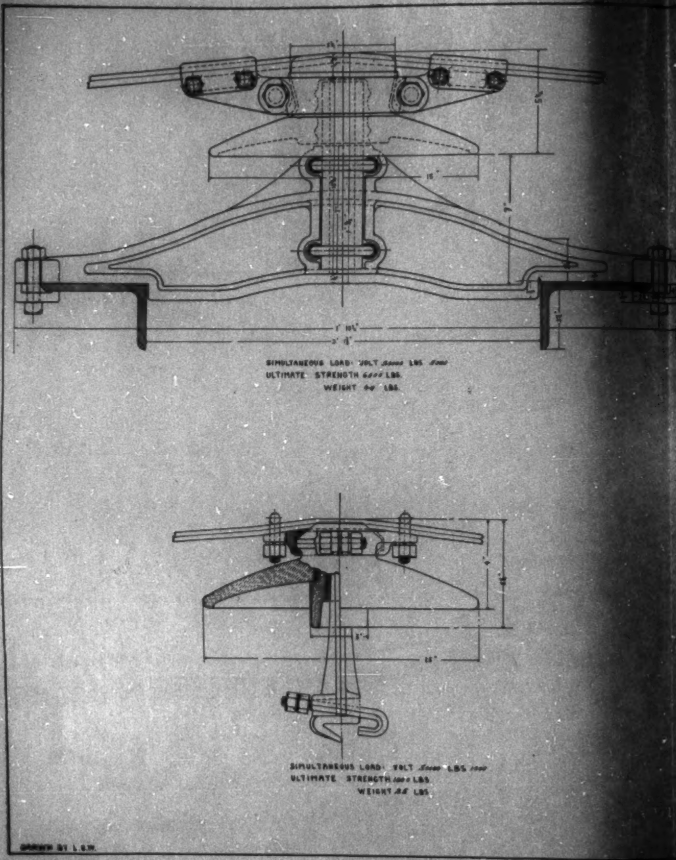
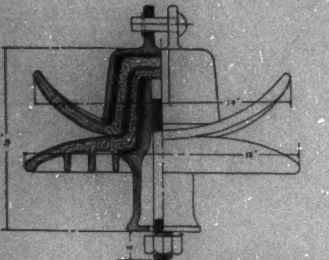

1' 10½"
2' 4½"
15"
9"
SIMULTANEOUS LOAD: VOLT 80000 LBS 6000
ULTIMATE STRENGTH 6000 LBS.
WEIGHT 40 LBS.
4"
3"
15"
SIMULTANEOUS LOAD: VOLT 50000 LBS 1000
ULTIMATE STRENGTH 1000 LBS
WEIGHT 25 LBS
DRAWN BY L.S.W.

FIG. 59.—Supporting in



SIMULTANEOUS LOAD: VOLT 110,000 LBS. 4000
ULTIMATE STRENGTH LBS. 6000
WEIGHT 40 LBS.

N.Y.N.H. & H.R.R.
ELECTRIFICATION
CATENARY CONSTRUCTION
SCALE 6" = 1'-0" MARCH-3-1911

SUPPORTING INSULATORS
USED FROM 1908 UP TO FEBRUARY 1911

59.

(Murray 1446i.)

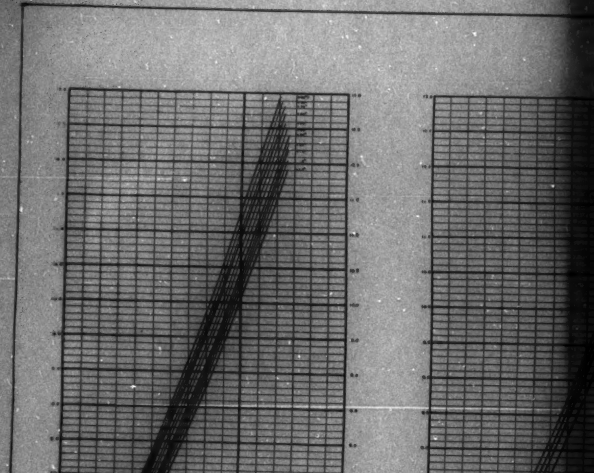
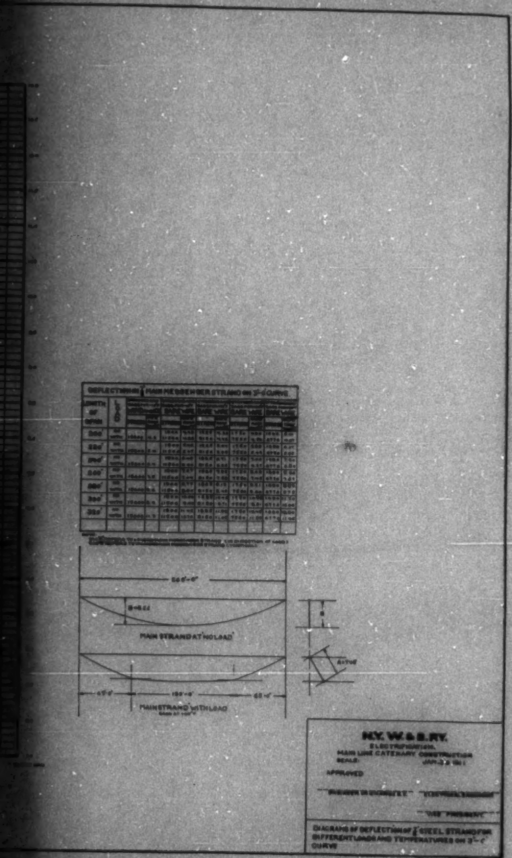


FIG. 60.—N. Y. N. H. & H. defle


DEFLECTION OF MAIN MESSENGER STRAND ON 3°-0 CURVE
MAIN STRAND AT NO LOAD
MAINSTRAND WITH LOAD
N.Y. W. & B. RY.
ELECTRIFICATION.
MAIN LINE CATENARY CONSTRUCTION
SCALE:
JAN 26 1911
APPROVED
VICE PRESIDENT
DIAGRAMS OF DEFLECTION OF STEEL STRAND FOR DIFFERENT LOADS AND TEMPERATURES ON 3°-0 CURVE

231

for loads and temperature

(Murray 1446j.)

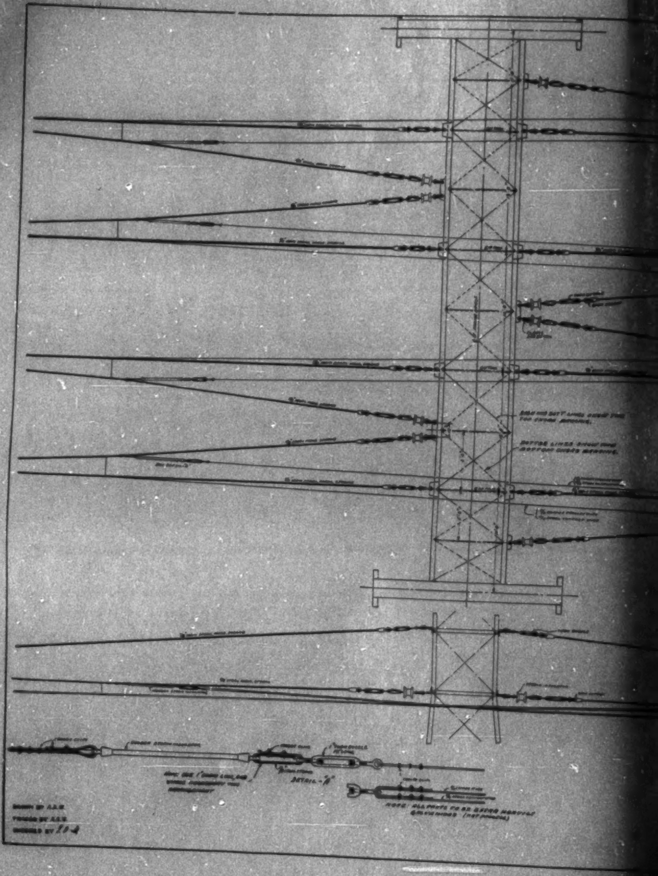
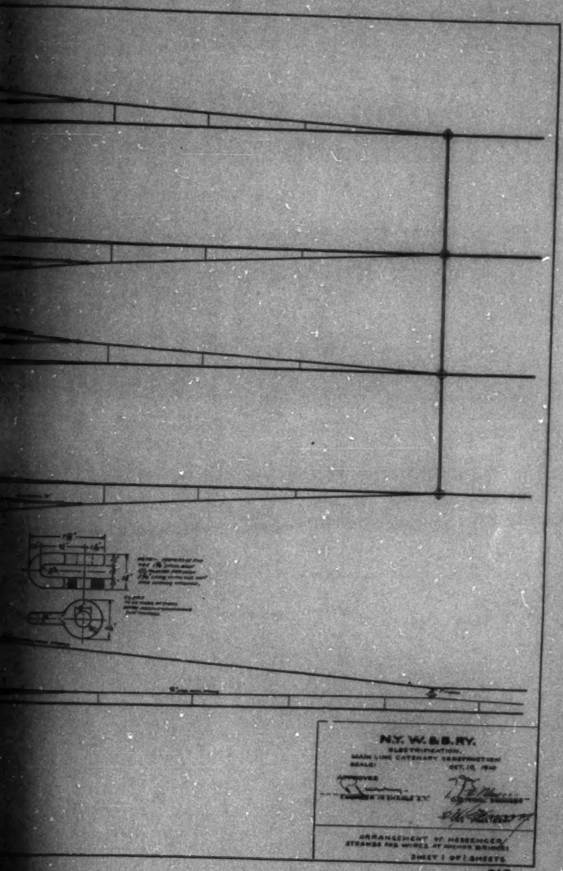

DOTTED LINES SHOW THE
BOTTOM CHORD BRACING.
DETAIL - "B"
NOTE: ALL PARTS TO BE
GALVANIZED (NOT PAINTED)

FIG. 61.—N. Y. W. &


N.Y. W. & B. RY.
ELECTRIFICATION.
MAIN LINE CATENARY CONSTRUCTION
SCALE:
OCT. 15, 1910
APPROVED
ARRANGEMENT OF MESSENGER STRANDS AND WIRES AT ANCHOR BRIDGES
SHEET 1 OF 1 SHEETS

215

or bridges

(Murray 1446k.)

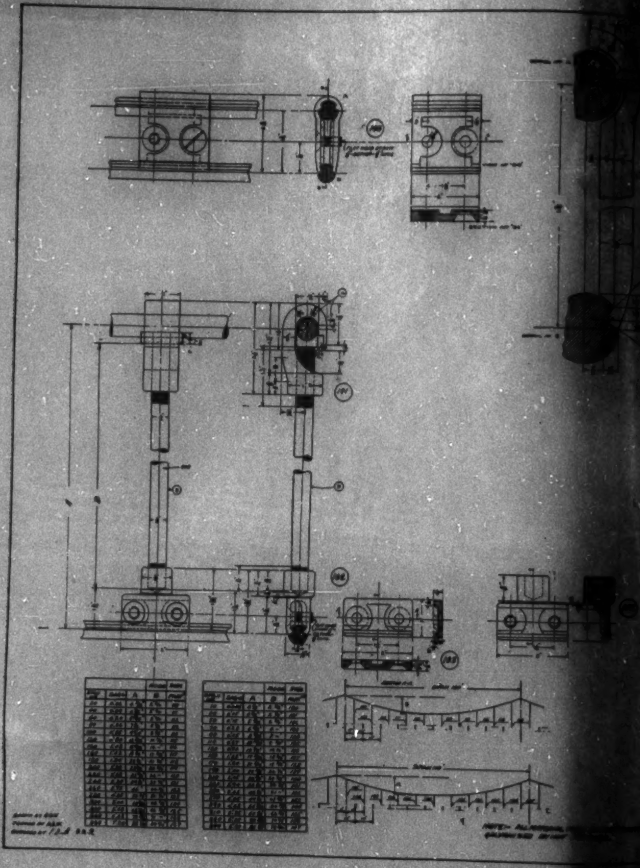
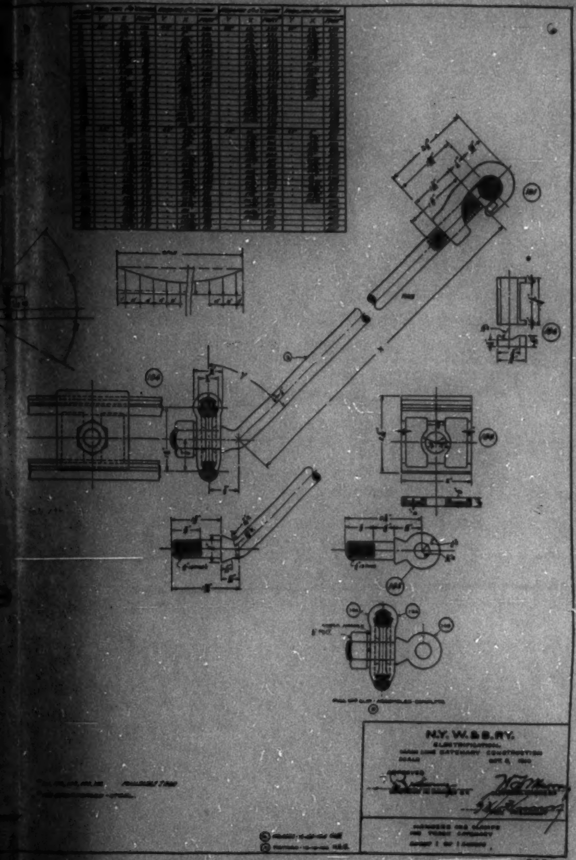


FIG. 62.—N. Y. W. &


N.Y. W. & B. RY.
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION

214

ent and curve catenary hangers (Murray 14461.)

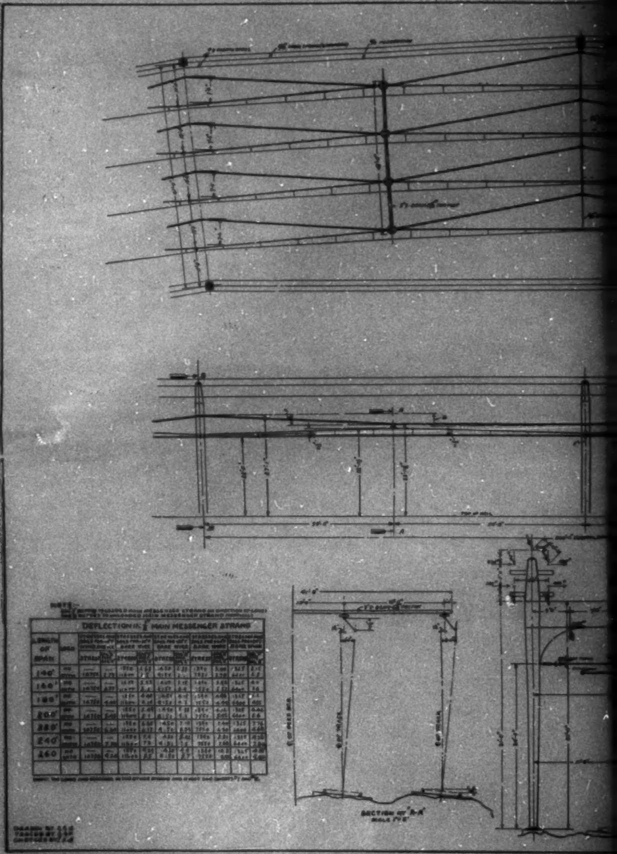
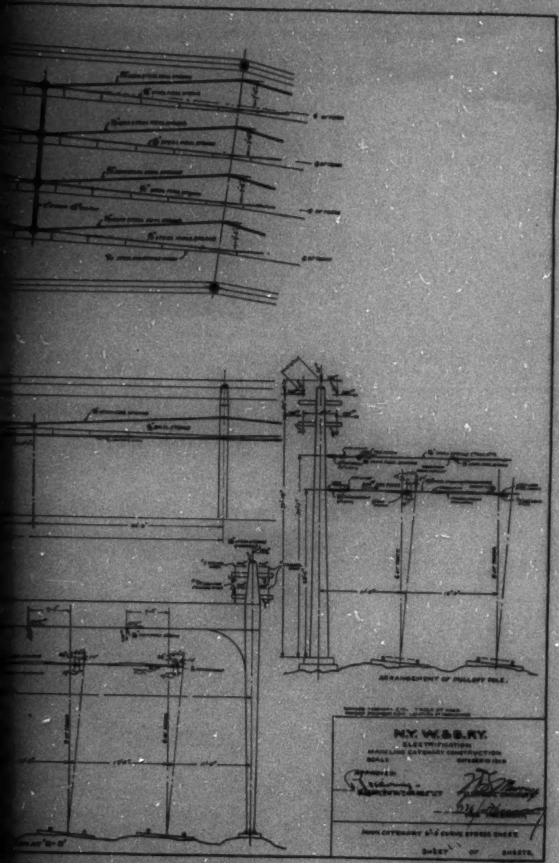

DEFLECTION IN 7/8" MAIN MESSENGER STRAND
LENGTH OF SPAN
140'
160'
180'
200'
220'
240'
260
SECTION AT "A-A"

FIG. 63.—N. Y. W. & B. deflection a


ARRANGEMENT OF PULLOFF POLE.
N.Y. W. & B. RY.
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION
SCALE
APPROVED:
MAIN CATENARY 6°-8' CURVE STRESS SHEET
SHEET OF SHEETS.

213

r curve catenary construction

(Murray 1446m)

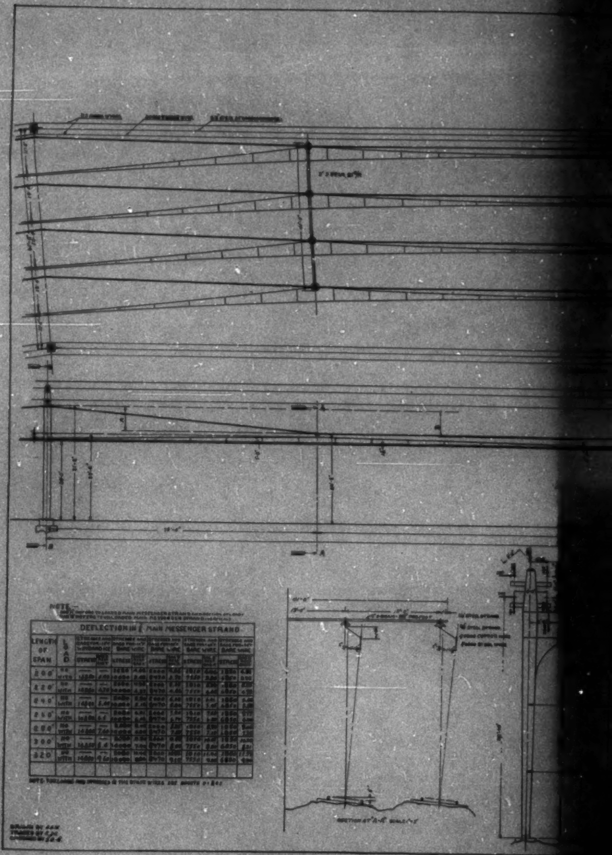
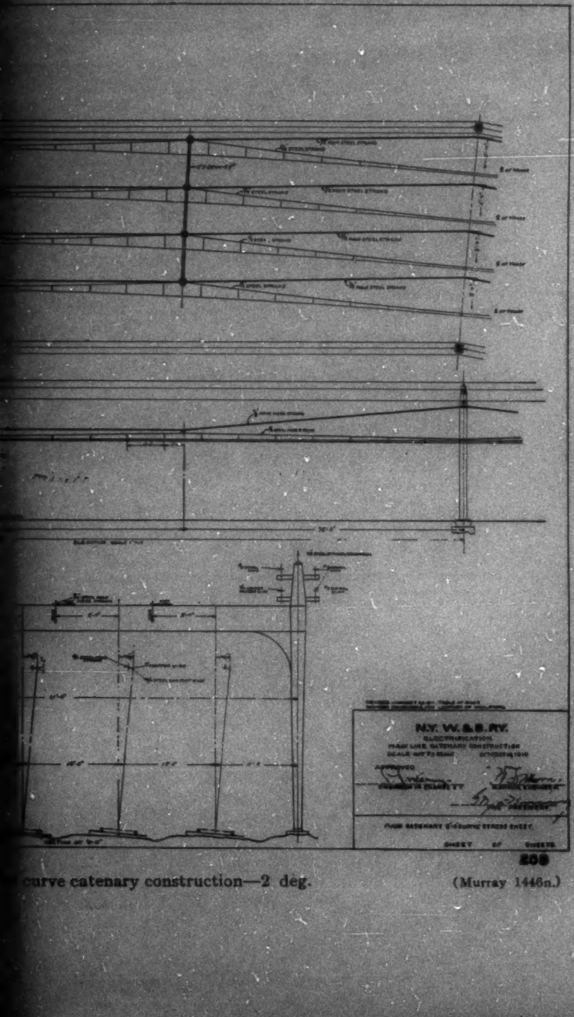

DEFLECTION IN ℄ MAIN MESSENGER STRAND

Fig. 64.—N. Y. W. & B. deflections a


N.Y. W. & B. RY.
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION
SCALE NOT TO SCALE
APPROVED
SHEET OF SHEETS

209

curve catenary construction—2 deg.

(Murray 1446n.)

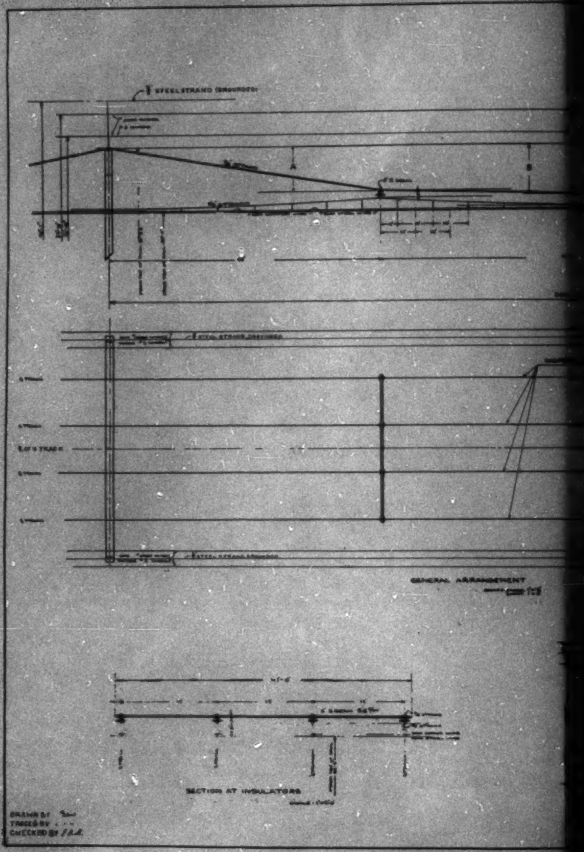
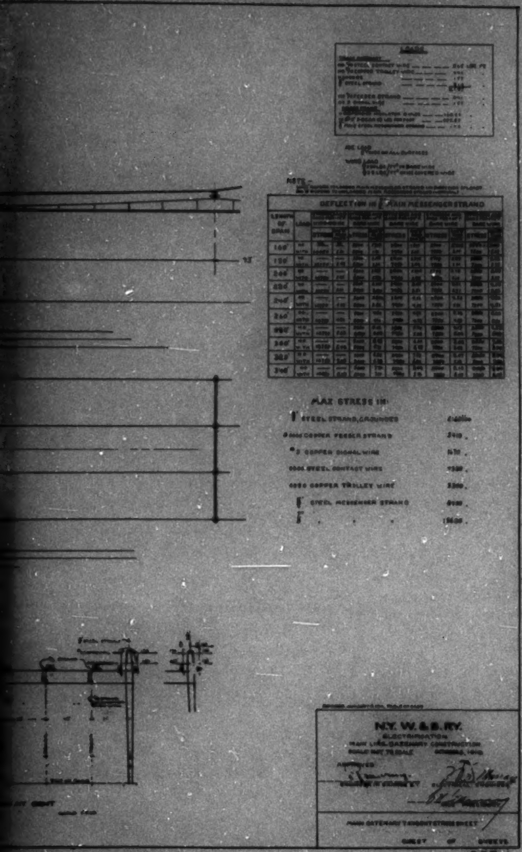

STEEL STRAND (GROUNDED)
A
B
C OF TRACK
STEEL STRAND GROUNDED
GENERAL ARRANGEMENT
SECTION AT INSULATORS
DRAWN BY
TRACED BY
CHECKED BY

FIG. 65.—N. Y. W.


DEFLECTION IN MAIN MESSENGER STRAND
MAX STRESS IN:
STEEL STRAND, GROUNDS
COPPER FEEDER STRAND
3 COPPER SIGNAL WIRE
STEEL CONTACT WIRE
COPPER TROLLEY WIRE
STEEL MESSENGER STRAND
N.Y. W. & B. RY.
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION
SCALE NOT TO SCALE
APPROVED
ELECTRICAL ENGINEER
MAIN CATENARY TANGENT STRESS SHEET
SHEET OF SHEETS

205.

ary tangent stress sheet

(Murray 1446o)

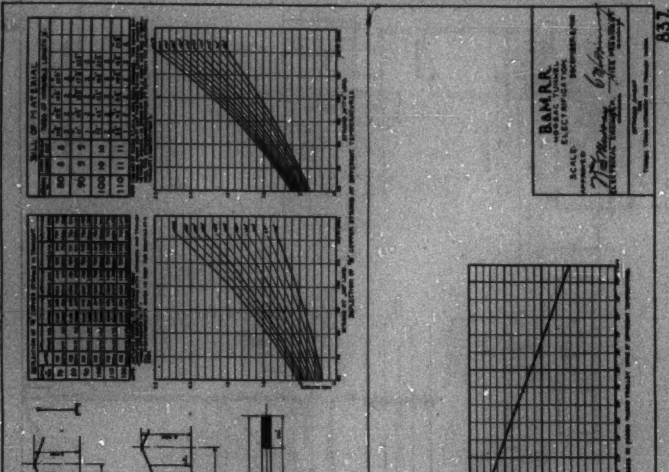

BILL OF MATERIAL
B.&M.R.R.
HOOSAC TUNNEL
ELECTRIFICATION
SCALE
APPROVED
837.

FIG. 67.—Hoosac Tunnel stress sheets for tunnel track catenary and trolley wires

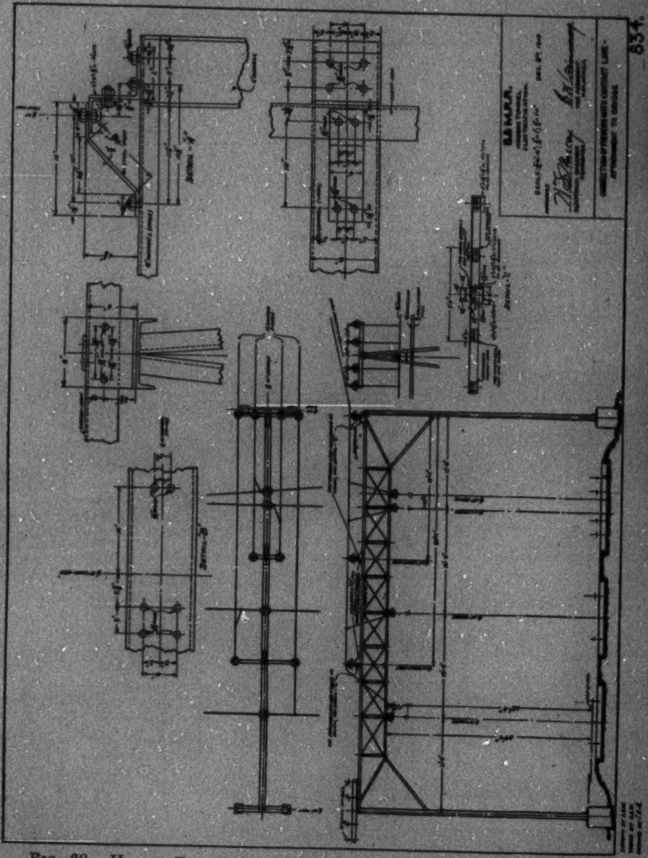


FIG. 68.—Hoosac Tunnel method of connection to contact lines

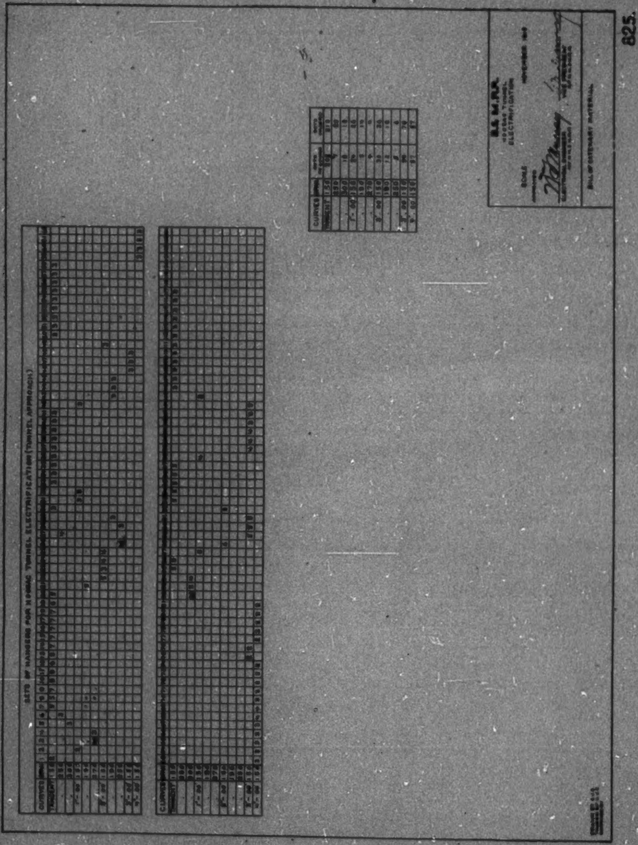


Fig. 69.—Hoosac Tunnel bill of catenary material

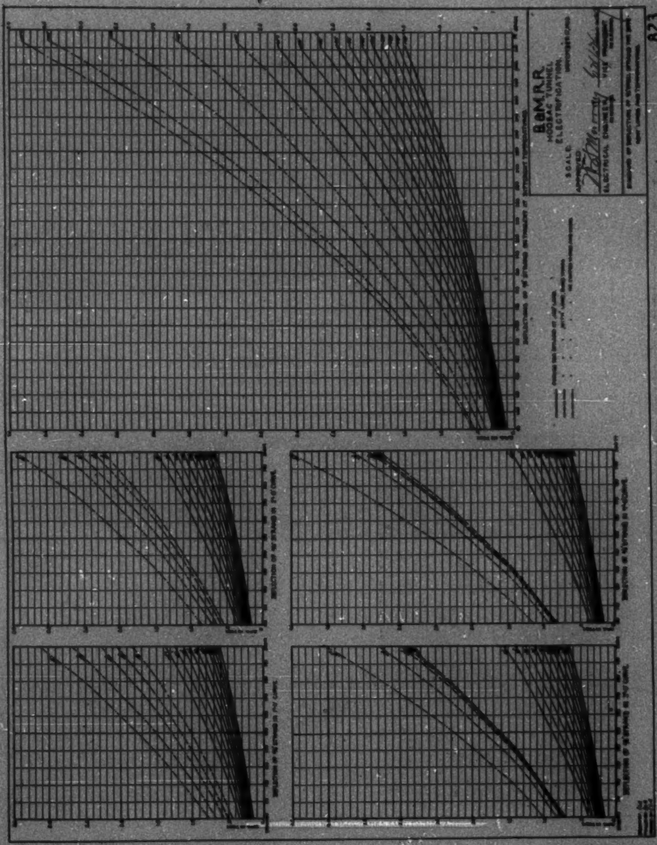


Fig. 70.—Hoosac Tunnel deflection sheet for different loads and temperatures

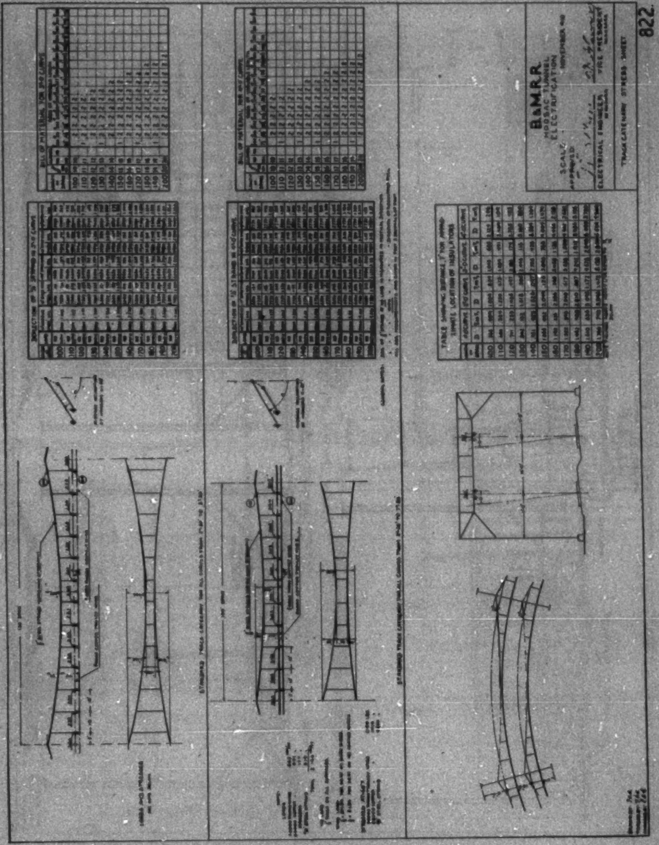

B&M.R.R.
HOOSAC TUNNEL
ELECTRIFICATION
SCALE
APPROVED
ELECTRICAL ENGINEER
VICE PRESIDENT
TRACK CATENARY STRESS SHEET
822

FIG. 71.—Hoosac Tunnel track catenary stress sheet

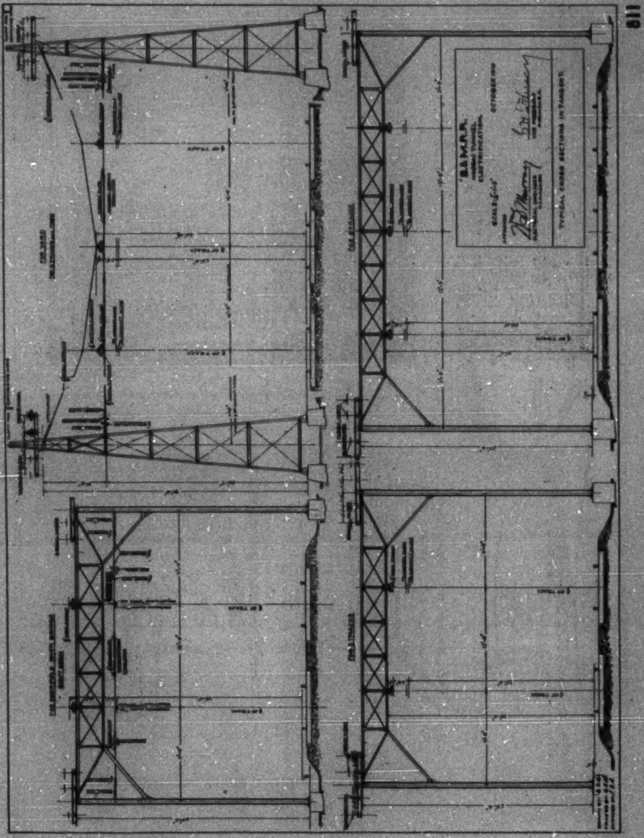


FIG. 72.—Hoosac Tunnel cross sections in tangent

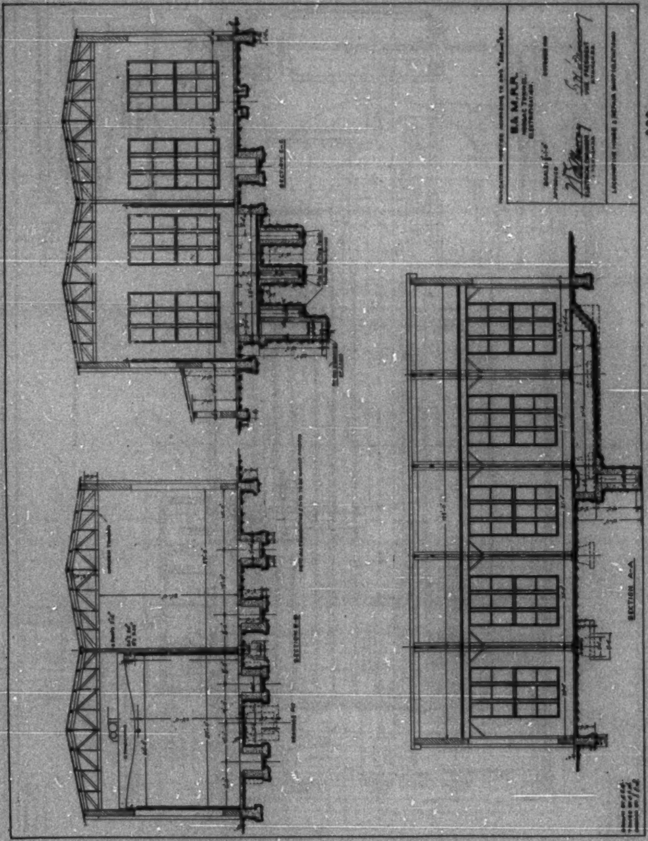

SECTION A-A
809

FIG. 73.—Hoosac Tunnel locomotive repair shop

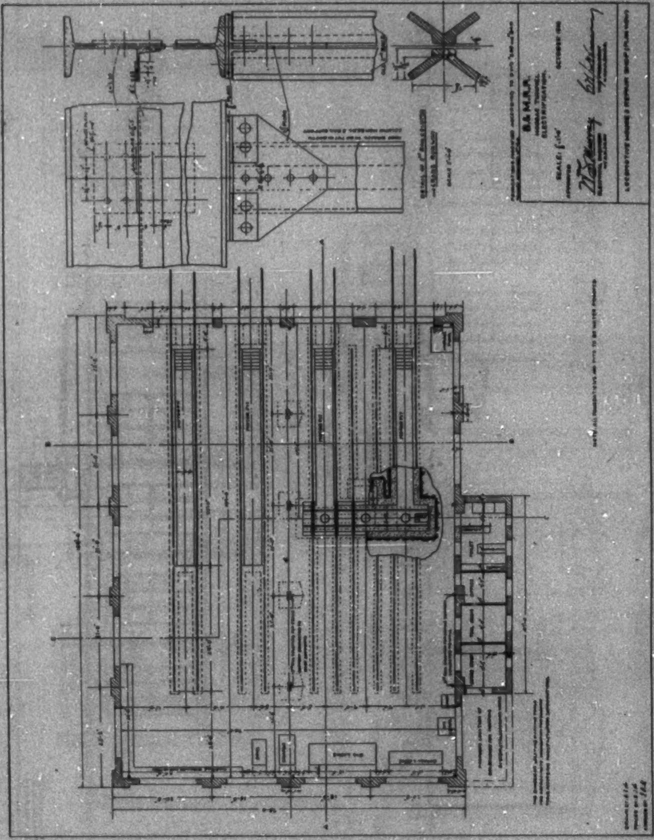


FIG. 74.—Hoosac Tunnel locomotive repair shops

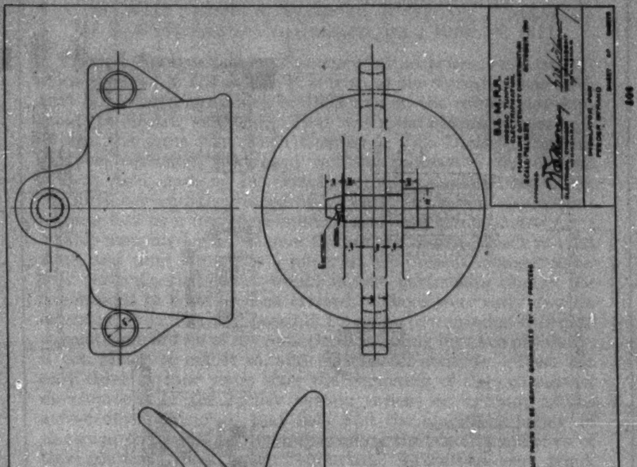

B. & M. R.R.
HOOSAC TUNNEL
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION
SCALE: FULL SIZE
OCTOBER 1910
APPROVED:
ELECTRICAL ENGINEER
VICE PRESIDENT
INSULATOR FOR
FEEDER STRAND
SHEET OF SHEETS
NOTE: ALL METALLIC PARTS TO BE HEAVILY GALVANIZED BY HOT PROCESS
MALLEABLE IRON
Corrugated Surfaces
MALLEABLE IRON
504

Fig. 75.—Insulator for feeder strand, Hoosac Tunnel

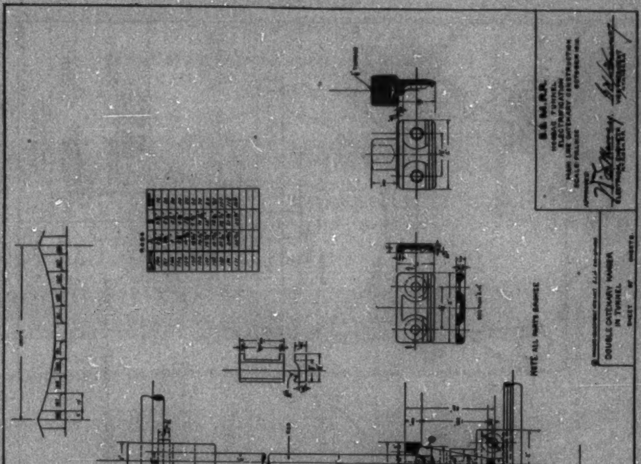

B. & M. R.R.
HOOSAC TUNNEL
ELECTRIFICATION
MAIN LINE CATENARY CONSTRUCTION
NOTE. ALL PARTS BRONZE
DOUBLE CATENARY HANGER
IN TUNNEL
SHEET OF SHEETS
805

FIG. 76.—Hoosac Tunnel double hanger

DISCUSSION ON "INDUCTION MACHINES FOR HEAVY SINGLE-PHASE MOTOR SERVICE," "ELECTRICAL OPERATION OF THE WEST JERSEY & SEASHORE RAILROAD," "ANALYSIS OF ELECTRIFICATION." CHICAGO, ILL., JUNE 28, 1911.

Frank J. Sprague: I have a somewhat proprietary and professional interest in Chicago. It is true, as the President has said, that my inaugural address in 1892 was on the coming developments in electric railways. That was some nineteen years ago. It was the same year when Charles J. Van Depoele, that ingenious, persistent and hard working pioneer in the electric railway field, gave up his earthly activities, and left his name, his influence and the record of his early work, but also a continuing loss to a new development and to a great industry.

This morning I glanced over the address which I made at that time, and were I to write a paper at the present moment upon this particular subject I would in few particulars change the conclusions at which I then arrived. Those were early days in electric railroading, and possibly I may be permitted at this date to quote one or two of my remarks illustrating my then prophecy, if you please to call it so, and my general attitude. That was only three or four years after the beginning of the commercial development of the trolley system, when, on account of the active development of that field and the ambitious hopes of electrical engineers and manufacturers, the electric railways of this country, city, urban, suburban, interurban and trunk lines, were in a few years to be converted to electric lines, and the knell of the steam locomotive sounded. It seemed to me at that time necessary to indicate the possible order of development of electric railways, and to utter a word of warning against undue optimism. Speaking of trunk line operation, I said: "Turning now to the greater powers, we must not confuse the terms "large powered" and "trunk line" work. They are two statements which I think will need no corroboration. If we had a continuous train movement completely occupying a track system, there can be no question but that its operation from a central source by electricity would be more economical than if operated by steam locomotives. So, too, if a large number of units in reasonable proximity are moved, and the starting and stopping so regulated that the total demand on the central stations is fairly continuous and equal, then there is no question as to economy of electric propulsion as compared to steam. On the other hand, the operation of a single unit or very few units over a long distance would be so uneconomical and afford so small a return on the investment required as to make it prohibitory. Between these two lies the condition of operation where steam and electricity meet on planes of equality; as the number of trains decreases steam operation is more economical, as the number increases electricity must be preferred."

I further said: "It seems to me the growth of electric railways will proceed something in this order:—First, the street systems in the various towns, then connecting lines between adjacent towns, following the line of highways, then along connecting lines, either on the track of existing steam lines, or growing bolder, on exclusive rights of way. Then will come suburban traffic on a large scale, and freight transfer systems, and finally the more ambitious project of trunk line service under limiting conditions such as I will specify. It has been very properly said that a man will make his first long ride on electric railways by transferring from one town system to another, through connecting links, rather than on individual roads."

As it was my privilege at that early date to here record convictions which time has confirmed, there is another reason why I should have a kindly feeling for Chicago. Ten years after the inauguration of the pioneer Richmond trolley road a combination of circumstances led me to develop the multiple unit train control system, and I sought, at my own expense, to make a demonstration of that system on the then steam operated Manhattan Elevated railroad lines in New York, because the system promised radical advantages in economy of operation and increase in capacity. Despite many attempts, I was not able to make it there, and it was not until the South Side Elevated Railroad in this City, having passed through the hands of a receiver, found it necessary to change its motive power to electricity, that I found an opportunity to demonstrate the value of my invention of multiple unit control. It was due to Chicago engineers, Messrs. Sargeant and Lundy, who gave me their personal confidence, and to the courage of the capitalists back of the railroad, that in Chicago was made the first beginning of that which has become now so vital and essential to all electric railway operation on a large scale.

Now, Mr. President, I presume Mr. Wood's paper has been presented in its order?

The President: Yes, all three papers have been presented.

Frank J. Sprague: I do not feel confident to discuss Mr. Alexanderson's paper. He has made an interesting suggestion for the use of alternating current with a split-phase device, by means of which, with a single phase supply, he can make use of the polyphase motor. As experimental developments are in a very active state of progress, I think it is useless to prophecy what the possible results will be, but rather to wait and see what the outcome is.

In considering present problems, let us note for a moment what the conditions were at the time I made my inaugural address. All work was then practically being done with direct current, with limiting potentials of from 400 to 600 volts. The direct current motor was being rapidly developed, but single phase and polyphase motors were almost unknown. The static transformer was just coming into use, and the motor generator had been introduced but was not meeting with any widespread applications. The rotary converter had been invented but was almost an unknown piece of apparatus.

The limitations, however, of direct current at the pressures then common had become manifest. I had already, some three years earlier, advocated much higher direct current potentials, which have been since materialized; and in the early days of electric lighting, when one of the local manufacturing interests was embarking in the developing of alternating current apparatus, I believe I was the first independent engineer to recommend to another corporation the necessity of alternating current transmission to supplement its direct current operations.

It has been stated that history is repeating itself, and that electric railway equipment will, therefore, follow a certain definite alternating current development. Quite probably history will in many ways repeat itself, but if so it will be along lines which are not exclusive, for that is not its usual habit.

Somewhat necessarily, it seems to me, there has arisen a difference between electrical engineers as to railway systems which has given rise almost to the establishment of certain cults, and the zeal of the advocates of each partakes something of religious fervor. Now the problem we have to face is very much like many others in the use of electric power. It is to generate and transmit energy with the maximum of reliability, convenience and economy, and then to use it in motors variously applied; the one thing which differentiates the railway problem from all others is that the motors are on moving vehicles, and hence the grouping is variable, both in amounts and distances from the source of supply, while the total power is oftentimes small compared with the distance over which it is distributed.

Were any particular feature of the problem to be discussed there would probably be little difference among engineers as to the best solution. For example, all would agree that the central power plant should be situated where the cost of construction and the supply of fuel and water, labor and incidentals would insure the maximum of reliability and economy; that such a plant should be equipped with turbines direct coupled to three phase generators, wound for a comparatively moderate potential, and operated on closed circuits. Transmission would likewise be by polyphase currents at potentials determined by local conditions, to which end, and for the providing of the proper potential at the railroad, static transformers would be the necessary adjunct at both ends of the transmission line.

They would also probably agree that provision must be made for supplying the railroad in such a manner that it could be sectionalized, both as to divisions and tracks, so that the entire system would not be disorganized and thrown out of operation because of accident to any part.

They would agree also that there is a variety of service to provide for—freight, through passenger and local and suburban services; and that some trains should be pulled by single locomotives, others by double headers, yet others by locomotives both at the head and in the body of the train, and still others operated by motor cars grouped into trains on the multiple unit system.

Again, they would agree that current must be supplied to the trains along the right of way by working conductors in the form of an overhead trolley, variously erected and supported, available for single or polyphase currents at all practical potentials and for direct current at much higher potentials than have been common, or in the form of a third rail, protected or otherwise, available only for direct current.

Coming now to motors, it would also generally be agreed that the polyphase motor has the highest weight-efficiency, and that the direct current stands next in order, while the single phase has less output per unit of weight than either of its rivals; that the polyphase motor requires besides the track two conductors, and has the limitation of constant speed, while the other two types of motors require but one conductor beside the track, and have variable speed characteristics. Both of the alternating current motors ordinarily would require static transformers on the locomotives, while for direct current operation rotary transformers or motor-generators must be used at the substations.

Also, in the United States, there are three alternating current frequencies in extended use, namely, twenty-five, forty and sixty cycles, and where a single-phase motor is used frequencies from 25 down to 15 only are practically usable, the latter being more favorable.

Taking all these various factors into account, the problem must necessarily be a compromise in settlement; but despite this fact, and the further fact that the supply of power for railway operation is but a fraction of that used for all purposes, many would differentiate the railway supply from all others and set up a standard for universal acceptance.

It is unfortunate that in so doing there is a disposition in many quarters to base comparisons upon arbitrary limits of development on the one hand, and unquestioning acceptance of results accomplished or promised on the other, despite the fact that engineers, the world over, when brought face to face with specific problems oftentimes arrive at different conclusions. It seems to me that this is a wrong attitude, and that the duty of the electrical engineer is to encourage the fullest development by every known system, so that he may, with open mind and in the full light of actual experience, decide for the best whenever he has to consider any specific problem, even if when some other is presented his decision may be different.

In short, while there are many things that can be or are standardized there are some things which in my judgment can not now, and perhaps never will be made universally exclusive.

As Chairman of the Railway Committee, therefore, it has seemed to me that we should have arrived by this time to a discussion of Steam *vs.* Electric operation, based upon known operating facts and known construction costs, whatever the system used; and I repeat the time is inopportune and the occasion unwise that brings up at present any discussion which attempts a present settlement of the question of this or that predominant system. To this end, I have continually urged the getting from existing corporations actual facts, not promises or predictions, but facts concerning operation in that same detail that we have for the operation of urban or interurban railways.

We have been passing through an experimental stage of exceeding importance and far reaching consequence. The single-phase development promised much, it has disappointed much; it has been watched with a great deal of interest with a desire to know the results. It received its first impulse in this country on the interurban railways, and the history of that development has been interesting. All installations here have been put in through the instrumentality of two companies. I am not entirely certain of my statistics, but of the six or eight single-phase equipments put in with the apparatus of one of these companies, one only is now in operation. Some of these roads have gone into the hands of receivers, as it is true other roads under other systems have gone, and direct current has taken the place of alternating current operation. Notably, there is the case of the Baltimore, Washington and Annapolis road, probably one of the largest and most influential examples of interurban operation which we have in this country, and one of the most suggestive.

Now we have in operation a number of roads on a sufficient scale to get operative facts, let them be what they are. We have in New York three great terminal equipments. There is the New York Central and Harlem, operating at 650 volts on direct current supplied from an under-contact rail, and the New York, New Haven and Hartford, operating from Woodlawn to 42nd St. on direct current, and from Woodlawn north and east to Stamford by the single-phase, with an overhead trolley. Both of these have a considerable mileage of tracks. There is also the terminal operation of the Pennsylvania Railroad into New York City, which is on the direct current system, and the extensive Long Island Railroad development, which may be considered essentially a suburban system, also aggregating a very considerable mileage. Then there is the West Jersey and Seashore Railroad, running from Camden to Atlantic City, a distance of about eighty miles, with a trackage of one hundred and fifty miles, converted a few years ago from a steam line into a direct-current system.

Whether from fear of the Interstate Commerce Commission, or the demands of commuters, or because of certain unsettled conditions, or because possibly the circumstances are such that they do not care to have it impressed upon them that electrification might take place elsewhere under other conditions—railway officials have manifested a great reluctance to give the actual facts as to costs of operation, not predictions of what may be sometime, but what, under the existing exigencies of the service are the actual facts at the present time.

Of course, this operation is dependent on a number of factors, and the first is the cost of creating power, of which we have heard so much—in short, the operation of the power station. This is a factor which has become pretty well known in its characteristics, its cost, reliability and what not, on all ordinary electrical work, but which for some reason or other, has been kept with extraordinary secrecy from the ordinary knowledge of interested engineers where it applies to these larger trunk line installations. I do not intend to unduly criticise that attitude, although I think it is a mistaken one.

During the past year, therefore, I have bent my energies to find out if it were not possible by some means, through some channel, to bring out the facts, so far as they can be brought out, for comparison; because, after all, it is facts we want, not theory. Comparison of power house operation has for sometime, it is true, been privately made in great detail, and for mutual advantage, at the Port Morris, the Long Island and the Westville power houses. Later there has been added the Jersey City and Marion plants. Up to December, 1910, those were the only ones of these large railway power houses (I should have included the Interborough of Manhattan) which were making direct comparisons. I believe that in February last the New Haven consented to coöperate in making these private comparisons. But, really, why should not all, and freely, make public the facts?

Mr. Wood's paper was originally compiled for the purposes of presenting to the general manager of his division the facts contained therein. The Railway Committee of the Institute asked Mr. Wood if he would not request, as a courtesy and privilege, his general manager to allow the actual facts of the cost of operation of that railroad, as contained in the paper, to be presented at this meeting. Mr. Wood was fortunate enough to get the consent of his superior official to that publication. It has, I believe, set an example which other railroads must follow in time. Mr. Wood's action not only is highly creditable to his capacity and his persuasive powers, but the presentation of facts which he has made will prove in the end one of the most important, because of its initiation in getting at results, which has ever been laid before this Institute. I think that the thanks of the Railway Committee and the members in general are due to Mr. Wood for having been able to present these facts as he has, and to have done it with such perfect frankness.

I will not hold our electrical engineers entirely responsible for the lack of information. They are, after all, the servants of the railway officials, and railway officials, sometimes I think mistakenly, sometimes rightly, think perhaps the time is not ripe, the extent of operation not sufficient to justify them in making public the actual facts of the operation. But it seems to me, after all, we as engineers can differentiate the various factors that go to make up these reports; and when a railway official gets that opinion into his head then we may be trusted with some degree of confidence in dealing with the facts when laid before us.

Mr. Wood's paper has some features to which I wish to call particular attention. The time of installation occupied only seven months, a most creditable performance. The power-house report for 1910 makes the cost per kw-hr. .542 cents, a creditable result under the circumstances. In passing, it is of interest to note that at the Jersey City and Marion power stations, although there is a difference in year 1910 of nearly one hundred per cent in the basic cost of coal, there is a difference of only eight per cent in the cost per kw-hr., and the actual cost is less with the station which used the higher priced coal, but not for that reason. The transmission efficiencies from power house bus-bar to substation bus-bar on the Westville line increased from 72 per cent in 1907 to nearly 82 per cent in 1910. That makes the power cost at present 0.542 cents per kw-hr. at the central station and 0.646 cents at the substation; and the cost of operating the substations based on this output is 0.108 cents per kw-hr.

The total cost of operation per car mile in 1910 averaged something over 18 cents, varying from a little over 12 cents to nearly 25 cents per car mile, a variation which is affected by frequency of service, density of movement, and the use of current for lighting, heating and various other purposes. While there was this variation of nearly 13 cents in cost per car mile, the cost of power delivered varied less than 3 cents. Out of the 18 or 19 cents average total cost per car mile of operation, of which only 3½ cents represented the cost of power, the cost of the sub-station attendance, maintenance and upkeep was three per cent of the total. The upkeep of the high tension transmission line was something over $4.00 and the third rail $6.50 per mile, while the upkeep of the trolley was six times that of the third rail per mile.

Coming now to Mr. Murray's paper, it is somewhat difficult for me to treat it with the thoroughness which its voluminous character and its wide dissemination would ordinarily be expected to require. What was hoped for, and is needed more than all else, is that presentation of actual construction and operating costs so vital to any intelligent consideration of the subject of steam railroad electrification by any means whatever—not a special plea for a particular system, no matter how ardent its advocate may feel in its behalf.

I doubt not that among the many engineers of occasional conservative tendencies—the natural result of some years' experience in spending one's own and one's client's money in industrial development, and sometimes seeking an acceptable excuse for a dearth of dividends in times of increased cost of living—I am included (to borrow Mr. Murray's description) among those "who claim some recognition in the field of railroad engineering," and who believe that the time has not yet come, if indeed it will ever come, when the electrical engineer, in his broader responsibility, can say that there is but one system of electrification adequate to meet all the varied problems of railroading.

Certainly such cannot be said, with any degree of lasting authority, at the present moment; one might as well say that we have reached the limit of the tireless activities of the myriads of workers in the electrical fields, and that the curtain has fallen on new discoveries and inventions. Equally mistaken would be the claim that all railroads are ready to be electrified, or on the other hand that none are, or that a hard and fast line of demarcation can be drawn between those which should and those which should not consider a change of motive power.

The author has presented many interesting isolated facts, some of undoubted value, and varied such presentations with a plentitude of drawings from the all-embracing and constantly accumulating records of the New Haven engineering department. But one looks in vain for some correlated and definite facts as to the costs of construction and costs of operation, either individual or comparative. Even the simplest facts as to cost of overhead installation, of locomotives and motor cars, or costs of power production and distribution, or of locomotive and motor car repairs and upkeep are not given.

I will take only a few moments to touch on one or two points in Mr. Murray's paper. There is here presented, what? Not the single-phase system, as ordinarily understood, but what I may call the author's system. I think it can be all found in his two earlier papers. What are the characteristics of the system? Single-phase transmissions at a potential limited by the requirements of the trolley wire, from central stations equipped with generators built with variable voltages and operated with grounded circuits; the abolition of step-up and step-down transformers, thus giving up the absolute and necessary freedom of determining economically the potential of long distance transmission from a central station; a potential of 11,000 volts or higher on a trolley line in contiguous territories, but with entire freedom to change that potential to something different on remote lines; the abolition of the single-phase, 25-cycle motor, and the substitution therefor, as a possibility in the near or the dim future, of a single-phase induction motor, or in lieu of that the much criticized direct current motor supplied by a mercury rectifier or its equivalent. Furthermore, we have 25 cycles as the preferred frequency. In this last, Mr. Murray is somewhat at variance with the practical experience and recommendations of some others. We find the German, Swiss, Italian and Swedish engineers, and one of the great manufacturers of this country, who supplied the apparatus for the New Haven road, recommending, where alternating current is to be used, about fifteen cycles as the proper standard for trunk line operation, while many of our prominent engineers in this country, men of wide experience and ability, and prominent in this Institute, endorse 25 cycles. We find eminent engineers abroad recommending polyphase apparatus entirely, others prefer single-phase, and here we have some who believe in developing the direct current to its logical limits so that what it can accomplish may be safely and fairly measured in comparison.

Mr. Murray says, "We have made the system work, now let us make it pay." After you have made a system reliable, and within its possible economy workable, the way to make it pay is to get traffic, and also to extend the use of the system to an engine division. Mr. McHenry, Vice-President of the New Haven road, is quoted as saying that, after all, if the passenger service can be operated by electricity, every wheel on a division ought to be turned by electricity; and he points out the important fact that the schedules of the freight operation can be so arranged as not to materially add to the burden of maximum demand on the central and substations. It seems to me that this latter day suggestion to operate every wheel of a division by electricity is very familiar. When the New Haven system was put in I said that if there is any reason for the adoption of this system on the New Haven road, even within the limits of the electric zone, the operation should be extended to every wheel, that passenger trains, multiple unit and through, and freight trains should be operated electrically; in short, one should be able to get the diversity factor on a railroad as well as elsewhere.

But I am going one step further. I am one of those who have a sort of growing belief that that diversity factor should be extended, and those who went yesterday afternoon to the magnificent Commonwealth Edison Company stations, and saw single generators of a continuous capacity two or three times the average power consumed the year round on the West Jersey line, and know something about the diversity of service on these plants, must realize, it seems to me, that the day of individualizing the railroad as we are in the habit of doing will pass, and that its demand for power, with increasing reliability of central station operation, will be met by great central stations connected up together, and further, that these central stations will be engaged not only in supplying electricity to railroads, but for every purpose for which electricity can be used within the radius of their operation. The New York Central and the New Haven roads could be supplied today, and supplied with less money, without one dollar of investment in central stations, by a general station of the capacity, size and system of operation of that of the Commonwealth Edison Company.

This statement has a bearing directly on the situation in Chicago at the present time. Here are more than a score of railroads entering the City, and an attempt to issue a mandatory decree by the Council that there must be electrification of these lines within the city limits within a certain time. I am opposed to mandatory legislation of that kind, but when electrification does come it will be for the engineers in charge to determine it. Then they should keep one problem in mind: How can the maximum benefit be obtained with the minimum of burden to the railroad and the community? That will mean a consolidation of power plants, so that the current will be supplied from a limited number of well situated distributing centers which will provide not only power for the railroads, but for everything else within the radius of their action. I think that this means polyphase transmission, and quite likely direct current distribution.

We have had one or two criticisms of the storage battery. Most people do not know why the battery was put in on the New York Central railroad, of whose Committee on Electrification I was a member. It was installed on the advice of every member of the Commission, because of the then absolute necessity for the fullest measure of insurance, not because we expected to lower the kw. cost much. We cut out part of our generating equipment, and spent $1,000,000 for batteries, and increased the then reliability of the plant from a practical point of operation by a large margin. There have been times when that insurance was worth a good deal of money. There are in New York and Chicago two of the greatest central power stations for general supply in this country. I believe there are not less than 40 to 45 batteries in the New York City plant, and a correspondingly large capacity in storage batteries in the Chicago plant; and if you ask the managers of these stations what is the use of the battery, they will tell you that it is not for the economical production of power, but for the insurance which the battery affords. I do not know to what extent storage batteries may be used on railroads in the future. The increase in the general reliability of central stations and in the limits of rotary converters are such that sometime we will not need a battery, but if a battery is to be used, remember that it is for insurance; do not go on the mistaken idea that it is put in to materially lower the cost of power, all things considered. When it is used it is applicable to direct current distribution, and not to single-phase distribution except by the introduction of moving apparatus of the full required substation capacity.

The time is so limited that some notes I have made I shall pass by for the present, but I wish to impress on you all my conviction, and I believe I have some right to express a conviction in a matter to which I have given twenty-five years, that the battle should be between steam and electricity and not between systems. I say, "God speed" to advance by whatever system, be it single-phase, polyphase or direct current, but when the merits of systems are discussed, I for one will always stand absolutely opposed to fatuous comparisons which accept all the promises of the one and deny the possibilities of the others.

Edwin B. Katte: I have not had an opportunity to read Mr. Wood's paper with the care that is necessary to discuss such a paper in detail. The real value of his paper is as an incentive to draw out similar operating information, and I will be glad to coöperate with the Railroad Committee in an endeavor to obtain more such data. I was sorry to note on the very first page that there would be no comparison with the cost of steam operation. We do not yet know the relative cost of steam and electric operation on trunk line railroads.

Among the very interesting points which attracted my attention was the comparison of the third-rail and the trolley systems. Mr. Sprague has already called attention to the fact that the trolley per mile costs six times as much to maintain as the third-rail. Again, in Table 8, we find that the detentions due to all third-rail troubles were twenty-eight minutes, and to the trolley troubles they were one thousand nine hundred and twenty minutes. At another point the first cost is given, and it is interesting to note that the cost of the overhead trolley is almost exactly the same as the cost of the third rail.

L. C. Fritch: I do not expect to talk to you this morning from the standpoint of an electrical engineer, but rather from the standpoint of the steam railroad engineer. I am very glad now, as a member of this Railroad Committee, that I did not prepare a paper for discussion at this meeting, seeing how Mr. Murray's paper is being criticized, but I will say that I did prepare a paper on the subject of the electrification of steam railroads as applied to terminals, but it was so proelectric, that when the railroad men received it it was suppressed. One President of a railroad said—"You are too enthusiastic on this subject, you have too much electricity in your system, and your views are too advanced. But from the investigation I have made so far I have reached this conclusion—" that there is work in transportation in heavy trunk line service that the steam locomotive cannot perform, but there is no work in transportation on heavy trunk line service that an electric locomotive cannot perform more efficiently than the steam locomotives. While I am not as narrow minded, I think, as some railroad men, I am certain it is possible to demonstrate that phase of the question when considering the application of electricity to heavy trunk line service. It seems to me that railroad men are making a mistake in endeavoring to ward off something that is inevitable. The recent development of the Mallet type of locomotive, in my opinion, is the dying gasp of the steam railroad men to maintain steam as a motive power on railroads. When we consider the Mallet type engine, weighing 615,000 lb., total weight, the weight on drivers 550,000 lb., with a tractive effort of 137,500 lb., and a ratio of pounds on drivers and tractive effort of 4, and then take the Pennsylvania railroad type electric locomotive of the passenger type, total weight of 332,000 lb., weight on drivers 207,000 lb., and tractive effort of 69,300 lb., and then take into consideration the overload capacity and the ratio of driver weight to tractive effort per pound, of 3, I think the argument is in favor of the electric locomotive. The railroads in this country have spent millions of dollars in grade reduction, line revision, and tunnel excavation, which, if it had been spent for electrification of these lines, in my opinion, in many cases it would have shown more economical results.

Now, as to the question in Chicago, the situation here is peculiar to itself and I am not altogether agreed with some of the statements made here this morning, that it is not a question of the systems, it is a question as between steam and electricity. It is true, it should be a battle between steam and electricity, but the question of the system must be established. As long as the system is not established, you are simply furnishing ammunition for those who do not desire to electrify.

The situation here in Chicago is this: We have some twenty-five trunk lines in Chicago. There is an interchange of freight traffic between all of them; the locomotives of one company go into the yards of every other company. Now, if one company should adopt one system, and another company adopt another system, it is readily seen how impossible the operation would be. I am an advocate of a universal system, or a system of systems that will be mutually interchangeable, and unless you make progress along that line, electrification is not going to make much advance in heavy trunk line service. In New York, of course, the situation is different from what it is here, but there is no reason why this question cannot be solved, and I think that instead of electrical engineers having a battle of systems, they ought to get together and devise a system or systems that will be mutually interchangeable.

Considering further the Chicago situation, which I think will be of interest to you, it has always appeared to me that the question has been approached from the wrong angle. It has always been a question of—Will it pay? While, of course, the financial question is the all-important question, yet there are instances in this city where electrification on certain branches of service will be justified, not as a whole perhaps, but an initial installation will pay, and that will demonstrate whether an extension of electrification will be justified. That, in my opinion, is the proper way to investigate the question here. There has recently been a Commission appointed to investigate the question in Chicago, and I do not think it will be difficult to write that Committee's report now, because statements have been made that it will cost $250,000,000 to electrify the railroads in Chicago. I do not agree with that statement. I think a sum half that amount would meet all the objectionable features of steam operation in Chicago today. The situation here demands not only electrification, an investigation into the matter of electrification, but a revision of the entire terminal situation. The railroad tracks in Chicago were laid principally as though shot out of a gun, without much system or relation to each other. What should be done, in my opinion, is that the railroads, as a whole, should get together and revise their terminals, and in my opinion, they should electrify them within certain reasonable limits; that common entrances should be provided and a group of passenger stations, with a joint entrance which could be electrified. If the freight terminals were made joint freight terminals, and all interchange traffic that has no business within the Chicago business district kept out of it, the local business could be handled in a much more simple manner than it is handled today and lend itself more readily to electrification.

There is one point that Mr. Murray has brought out, which I consider very valuable at this time, and that is the question of the electrification of switching terminals. In my opinion, that is one of the most important matters that has been brought out in these papers. He has shown that there is a possibility of a saving of at least thirty per cent in the number of units of switching locomotives. Now, take one railroad in Chicago having forty-five switch engines, a reduction of 30 per cent, would mean fifteen locomotives, and taking these locomotives at an average cost of $10,000 a year per locomotive, that would mean $150,000, which capitalized would mean $3,000,000. That will go a long ways toward electrifying a switching terminal. These are matters which we should bring out and develop, and wherever you raise the question of electrification, in railroad circles, you will be met with the statement that never yet has a large freight terminal been electrified, that it is not possible, and is impracticable in every sense. I do not believe that. I believe that in yard operation it is possible with overhead construction, using either direct current or alternating current, such as Mr. Murray figured out, and that it can be built for from $1500 to $2000 for single track per mile. It is not a question of the number of tracks. If you have a yard with fifty tracks, you can span these tracks, and that will remove all the objections to the third-rail or surface conductor which, of course, would be almost inadmissable in some instances. It would be possible to use a lower voltage in the yard that out on the main lines, where trolleys would be perfectly practicable.

J. L. Woodbridge: Mr. Murray in his paper states that storage batteries for trunk line electrification are not economical. He admits that a battery will permit more economical generation of power, but states that this increase in economy is offset by the increased output required (presumably to supply battery losses) and the cost of battery maintenance; and concludes his observations on this subject with the remark " It is of interest to note the passing of the storage battery theory; at least in as far as its application to trunk line conditions is concerned."

I desire to take issue with Mr. Murray on this point. So sweeping a statement would seem to call for a presentation of the facts and arguments upon which it is based. As it stands, it appears to be merely the expression of his own unsupported personal opinion. Without knowing the source from which it was derived, a comprehensive reply is impossible; but I would like to offer a few remarks on the other side of the question, and present a few actual facts in support of my position.

Inasmuch as Mr. Murray is evidently looking at the commercial, rather than the technical side of the question, I shall confine my remarks to that aspect of the matter. The question is, therefore, can a storage battery be so applied to trunk line electrification and so operated that the increase of economy in the generation (and possibly the transmission) of electrical energy will more than offset the cost of battery losses, battery maintenance and interest on increased investment, if any. I believe that in many, if not most, cases of trunk line electrification a complete analysis of the problem would show that a storage battery, properly adapted to meet the conditions and controlled to produce maximum economy, will be a profitable investment. In support of this position I would submit a few actual facts.

About three years ago, the Chicago City Railway Company entered into a contract with the Commonwealth Edison Company for the purpose of power. The details of this contract have been published, and are well known. It provides for the payment of a unit price per kw-hr. plus a service charge of $15 per kw. per year for the maximum peak, this peak being the average of the maximum one hour peaks of any three consecutive days. In order to reduce this service charge, the Railway Company, who already had one battery in service at 77th Street, installed another much larger battery at their Plymouth substation. As a result of the operation of these two installations, the saving in the power bills after deducting maintenance, operating expenses, rent, insurance, taxes, etc., is sufficient to pay 12 per cent on the investment. Now it will, of course, be contended that this result is due to the peculiar terms of the power contract, which penalizes the purchaser for peak loads to such an extent that the battery installation becomes a commercial proposition. This is very true, but if this power contract is fair and equitable to both parties in all its terms and conditions (and of this there can be no doubt in view of the standing and ability of the men who drew it up), if the terms of sale are logically based upon the conditions of power production, and the prices are truly proportionate to costs, then the battery investment would be equally profitable if the Chicago City Railway Company were developing its own power. In fact, it should be more so, since the terms of the power contract undoubtedly make it necessary for the Railway Company to discharge its batteries on peak loads on some occasions when there would be no economic advantage in doing this. If the Chicago City Railway Company were developing its own power it would be possible to reduce the amount of work which the battery is now called upon to do, and thus reduce the cost of maintenance.

The Chicago City Railway is not, of course, a case of trunk line electrification, but it will doubtless be conceded that trunk line service is still more favorable to the storage battery, in view of the smaller number and heavier demand of the train units, and the more irregular and intermittent character of the load.

The economy arising from the presence of a storage battery in connection with an electric system may be effected in two different ways.

First, a careful analysis of the cost of producing power under the various load conditions will show that not every kw-hr. is produced at the same cost, but that this cost varies widely at different times of the day, and under different conditions of operation. In general, the power produced below the average load line at a steady rate, for many consecutive hours, is developed at minimum cost, while the power produced for the short peaks above the average line, is produced at maximum cost. The difference between these two costs of power is actually much greater than many engineers are apt to realize. To develop energy at the minimum cost, and store it in a battery, to be again delivered to the system under conditions when the cost of developing the power directly would be a maximum is one method of deriving economical results from the operation of the battery.

The second way in which a storage battery can effect improved economy of operation is by its mere presence on the system as a reservoir of energy ready to deliver its output at a moment's warning under any unforeseen conditions of demand or power supply. The mere fact that such a reservoir is at hand, even though it be seldom called upon, will permit a more economical operation of boiler and engine room than would be possible if some other form of generating apparatus, such as boilers, engines and generators, must be kept in readiness for emergency service. The batteries installed in connection with the New York Central electrification are handled in this way.

A review of recent progress in storage battery engineering, and recent development in automatic controlling apparatus, will reveal a tendency to limit more carefully the operation of batteries to the particular class of work for which they are especially adapted, and to eliminate a large amount of battery work which does not make for economy. It is not economical for a storage battery to take *all* the peaks above and below a given average load line. Much of this class of work, which has heretofore been thrown on storage batteries where they have been installed, would be more economically handled by the generating apparatus. This fact is being more and more clearly recognized, and automatic controlling apparatus has been developed to discriminate between the different classes of fluctuations in such a way that only those peaks and fluctuations which can be economically carried by the battery, are referred to it. This means that the size of the battery may in some cases be reduced, the first cost decreased and the maintenance charge lessened. In any case the efficiency of operation is improved.

The use of storage batteries for stand-by service has also assumed greater prominence in recent years, and while this use is largely found in electric lighting systems, it is occasionally applied to railway work. The operation of the battery in connection with the Baltimore Tunnel electrification is in some ways an example of this class of service. The Baltimore and Ohio Railroad Co. has recently entered into a contract for the purchase of power from the Consolidated Gas, Electric Light and Power Company, under the terms of which the cost of power is increased by peaks and fluctuations above certain specified limits. The battery is operated to prevent the power demand from exceeding these limits. Under ordinary load conditions the battery is merely floating on the line, and is prevented from charging or discharging when such work would not have any effect in reducing the cost of power. When, however, the demand exceeds the limit set, the battery discharges, taking all load fluctuations above this limit. This operation, which may be called stand-by regulating service, is produced automatically by controlling apparatus recently installed. The result is that the battery is called upon to do only such work as is commercially economical. This is another instance in which the terms of the power contract between the user and the producer of power make the operation of a storage battery commercially economical. The terms of this contract are the result of a careful analysis of all the conditions of power production and utilization, this analysis being equally applicable if the operating company were producing its own power.

It may be interesting to note that in neither of the cases cited above is it a part of the battery's function to regulate the momentary fluctuations of load for the improvement of the lighting service of the company which is producing the power. The momentary fluctuations in both cases are ordinarily allowed to fall on the power company's system. Refinement of voltage regulation, which in some situations is the motive for the installation of a battery, is not called for in these two examples and the argument for the use of storage batteries in these cases rests on commercial economy only.

Dugald C. Jackson: The electrification project of the New York, New Haven & Hartford Railroad, for handling trains entering and leaving New York, has been a center of interest to all engineers having electric railroad relations; and the courage and vigor with which the engineering staff of that road attacked the problem of designing, constructing and adapting a then substantially untried alternating current system to meet the needs of an active steam railroad traffic has been a matter of satisfaction and congratulation to all. The accomplishment that has been reached in four or five years is remarkable, and is a monument to the fidelity and skill of the engineering staff which carried it out.

The drawings which accompany Mr. Murray's paper give concrete evidence of some of the work done and some of the difficulties which had to be overcome to make the working of the system a success. I speak of difficulties—they obviously were tremendous, and when faced in the course of work must at times have seemed nearly insuperable. Their spikes and claws appear relatively few and harmless when viewed in the retrospect afforded by this paper, but the credit to the engineers whose courage, foresight and ability wrought this result, should not be diminished. When we admire the courage evidenced by the New Haven Railroad organization, by the adoption and installation in service of its Stamford-Woodlawn system of electrification, and their skill in overcoming the appalling difficulties which faced them, we must also acknowledge that the adoption of 11,000-volt trolley construction in the wet and difficult conditions of the Hoosac Tunnel proves that their courage remains unbroken.

There is no longer any question of the physical ability of electric motive power to cope successfully with all of the problems of trunk line, suburban or terminal service, and with a reliability excelling the service by steam motive power. The only possible exception may be that of the railroad yard, but any one who goes to Mr. Murray's little yard—little to be sure, but effective—over which he now has wires, cannot but be impressed with the simplicity of the situation there. I have not yet had an opportunity to look at Mr. Murray's switching locomotive, but from what he tells me it must be remarkable for activity and perfection in operation. Not only that, but we now have the proof that electric motive power is satisfactory for the work of moving trains in trunk line service, (as we have heretofore had proof of its adaptability in suburban and terminal service), and this with a reliability obtained which perhaps excels and, at least fully equals the records of steam motive power. These proofs have been made in a few years. Having made these proofs in relatively few years, we are bound to see yet better results as more experience is obtained. Well built electric machines are acknowledged to be among the most reliable machines made by man, and the substitution of electric for steam motive power removes the least reliable part of the motive power of the railroads, that is, the engine and boiler, from the road, and establishes them in larger and better perfected units located in stationary power stations where they can be properly inspected, supervised and cared for.

The physical success of electric motive power has been abundantly proved in trunk line, suburban and terminal service, for single-phase, polyphase, and direct current installations, in this country and Europe. It is undeniable that several Swiss roads have made a success of electrification, but perhaps they are too small to be compared with some of the great trunk lines in this country, and I will not go into a discussion of them. The Valtellina road was one of the earliest steam railroads to convert to electric service, and its electric service has been successfully maintained for years. Various other Italian roads give evidence of success. The London-Brighton installation in England has sufficiently proved its justification. Neither is physical success deniable in the installations at the Cascade Tunnel of the Great Northern Railroad, the St. Clair Tunnel of the Grand Trunk Railroad, the relatively new Detroit Tunnel of the Michigan Central Railroad, the West Jersey and Seashore Line of the Pennsylvania Railroad which Mr. Wood described, the lines of the Long Island Railroad, the New York Terminal of the New York Central Railroad, which Mr. Katte discussed, the Stamford-Woodlawn zone of the New York, New Haven & Hartford railroad, which Mr. Murray described, and the relatively new New York Terminal of the Pennsylvania Railroad, and other important installations in the United States.

It is being urged in some quarters that electrification of additional lines or terminals on a large scale ought not to be pressed forward, on the ground that engineering in this branch lacks standards. The data contained in the papers presented this morning, it seems to me, prove the substantial baselessness of that assertion, notwithstanding the fact that one dealt with an alternating current installation and one dealt with a direct current installation. The baselessness of that assertion is equally proved by the standards of electrical construction and apparatus of the New York, New Haven & Hartford Railroad, the New York Central & Hudson River Railroad, and the Pennsylvania Railroad. The fact that electrification may be made by means of either single-phase, polyphase, or direct current does not signify lack of standards, but is a patent of the ability of electric power to meet every requirement when the system adapted for particular service is selected and installed with engineering skill. In a situation such as exists here in Chicago, it would as Mr. Fritch suggests be criminal for the important roads to adopt systems which are not freely interchangeable. Some minor road may have a different system on account of not coming into the main systems, but the equipment of all important roads entering a place like Chicago must be completely interchangeable. This however may be accomplished, and involves harmony in engineering plans to bring it about. The prime point is, that electrification allows a choice of motive power which will most effectually serve the purposes of the particular terminal conditions.

It would be palpably absurd to assert that no standards exist in steam locomotive practice because Atlantic type, Pacific type, Mallet articulated and other types of locomotives are in common service in different parts of the country, where different conditions are to be met. I presume, in fact, that electric motive power has come nearer uniformity in standards, young as electric service is, than practice with steam motive power has yet attained. The flexibility of electrical equipment is illustrated by the capability of the New Haven motors and controlling devices to operate successfully and alternatively over the New Haven's own lines with its 11,000 volt alternating current delivered to the contact shoe by trolley wire, and over the New York Central's lines with its 700-volt direct current delivered to the contact shoe by third-rail. An argument against electrification on the ground that standards and conditions of interchangeability are not being or cannot be provided where they are needed is obviously untenable.

The only open question about electrification, *i.e.*, whether the improved service which is inherent with it can be established and provided without enhancing the present cost of service, is not answered in Mr. Murray's paper, or wholly in Mr. Wood's paper; and rumors regarding the fiscal achievements of the important electrification projects operating in various parts of the world are not sufficient bases to afford conclusions. It is obvious that steam operated trunk lines of light traffic and unimportant terminals are not at the present time reasonable candidates for electrification, and the open question, therefore, relates to important terminal centers and to trunk lines and suburban lines with reasonably dense traffic. A number of good clues to the answer to this question are already available from papers which have been read before this Institute. Good clues are further available in the continued satisfaction given by the electric operation of certain of the Italian, Swiss, and French railways (some of them doing both freight and passenger business), besides the two or three in England, the reports that have as yet been made public regarding the fiscal success of the West Jersey & Seashore and Long Island Railroad electrifications, the St. Clair Tunnel installation, and perhaps others, in addition to the very persuasive example put forward by the New York, New Haven & Hartford railroad in planning extensions of their existing electrification, with which they have had several years experience and with which they appear well satisfied.

It is to be further observed that fiscal comparisons between the New Haven electrification and its well systematized steam locomotive service probably cannot yet be flatly made. The electrification has only recently emerged triumphant from the pains of a developing system to a point where Mr. Murray is prepared to say that it operates under commercial conditions. Somewhat the same is true of the New York Central & Hudson River Railroad installation. Indeed, both of these installations are operated under the expensive conditions imposed by reconstruction work going on at the New York terminal, which must temporarily add cost to the handling of trains. Under all these obstacles, electrification seems to have "made good."

N. W. Storer: There are a few points which stand out in Mr. Wood's paper that I should like to refer to briefly:

First. The excellent showing made in the extremely small number of detentions due to the motive power, as compared with those due to other causes. The fact that the detentions due to motive power and weather conditions together amount to only 8.38 per cent of the total number, shows a reliability of the service, which would be increased but little if all of the delays due to motive power were wiped out completely. It shows that until the delays due to general traffic conditions can be substantially reduced, it is useless to go to an enormous expense to reduce the already almost negligible delays, due to motive power.

Second. The data showing gradual decrease in the cost of power, indicating what can be done by scientific management, is certainly most encouraging. I discussed this matter with Mr. Wood, who stated that he had had some of his own men take charge of the power house and substations operation, with an immediate reduction in the cost of operation as the result. The rotary converters in the substation were operating practically all of the time in the earlier days of operation, and much of the time unnecessarily. They found it entirely possible to shut them down a good part of the time, and in this way reduced the light load losses, thus making a surprising difference in the power consumption.

Third. There are some points in connection with the operation of trains also tending to increase the power consumption which should be noted, one of which is the number of brake shoes that are worn out. In the year 1910 we note that there were 6300 brake shoes changed. It would be interesting to learn how many kw-hrs. were required to wear them out. One cannot help calling attention to the advantage in introducing the coasting time clock or some similar meter system, which will tend to increase the amount of coasting time, and therefore to reduce the speed at which the brakes are applied, and finally decrease the wear on the brake shoes and the power consumption. If brakes are applied when the cars are running at a speed of 50 miles per hour they must absorb practically four times as much energy as they would at 25 miles per hour, and it is probable that four times as much brake shoe will be worn off. A reduction in the speed at which the brakes are applied in ordinary operation will therefore effect a great reduction in the number of brake shoes, as well as in the amount of power consumed.

In discussing this paper, I think some of the speakers have gone out of their way to make unfavorable comparisons between the costs of maintenance of trolley and third rail. The advocates of any overhead trolley system might well be alarmed if the costs of maintenance given in this paper were characteristic of all the overhead trolleys, but fortunately such is not the case.

The idea that we gather from the paper is that multiple unit trains with wheel trolleys, operating under certain conditions, at high speed, over a rigid cross-span construction, are very destructive to the overhead system. Anyone who is at all familiar with the cost of maintenance of the overhead trolley system of an ordinary interurban line would know at once that the cost of $440 per mile, as given in this paper, is extremely abnormal. Wheel trolleys are made at the present time that will operate safely at high speeds on a good overhead construction. The roller pantagraph, as well as the sliding pantagraph, will also operate well. The roller is now used quite extensively on the Pacific Coast, and with success. The use of such a trolley would unquestionably practically wipe out the cost of maintenance of the overhead trolley wire, as well as some of the numerous delays noted. The cost of the maintenance of the third rail is very reasonable—in fact, is lower than most third rail systems, because it is of the simplest form used. It is a good, substantial third-rail construction, but it is not protected, and this fact decreases the cost of maintenance.

I am very sorry Mr. Katte did not give us the cost of maintenance of the New York Central third rail system. This is practically the best protected system at present in use, and some information in regard to the cost of maintenance would be very illuminating. I do not recall that any figures have ever been published in regard to this, and I am sure that such information would be very valuable to many members of the Institute.

After reading Mr. Murray's paper, I am more than ever impressed with the thought that if the events of the last two years have shown anything, they have shown the unwisdom of making such dire prophecies as were freely made at the time the single-phase system was installed on the New York, New Haven & Hartford Railroad. It seems to me that any system which has so many advantages and possibilities as the single-phase system should have the united efforts of all engineers concerned in developing them at the earliest possible moment.

Now in regard to this question of standardization. I believe that both Mr. Murray and Mr. Fritch are right—we must have some degree of standardization before the great work of electrifying railways goes much further, and this can only be accomplished by getting together. I do not mean to say by this that we must immediately unite on the single-phase system for all future work, but I mean that an effort must be made to get the most out of each system that is proposed. I wish it understood in this connection that I am not prejudiced in favor of the single-phase system. I am personally engaged in the development of designs and the manufacture of apparatus for operating on all of the different railway systems, and in that way am making every effort to make the best out of each one of them. I have advocated in the past, and am still advocating, the single-phase system for use in certain places, but have never ceased to believe that the apparatus designed for the 600-volt direct current system is the standard for reliability. Having had a wide experience with all systems, I feel that I can give an unbiased opinion. All I wish is to see the best system adopted. We must have a certain amount of standardization, especially for cities like Chicago, where the motive power must necessarily be interchangeable on all of the roads, and we engineers should get together very soon and get something settled.

I want to emphasize the point Mr. Murray has made in regard to the advantage of the electric locomotive for switching service—a service in which it has been used comparatively little. It is ideal for that class of work, and certainly will be used a great deal in the near future.

FIG. 1

At the time the passenger locomotives now in use on the New Haven Railway were built, both the railway company and the manufacturers of the locomotives were severely criticized because of the weight, and the fact that it was necessary to use two locomotives for hauling the heavier trains. This matter of course has been explained many times. I mention it only to call attention to the improvements which have been made since the first installation, in the capacity and weight of locomotives. In my discussion of Mr. Murray's paper at Toronto, I mentioned the new type of locomotive which has been built for the New Haven Company. It has quite radical electrical, as well as mechanical, features. The general view of this locomotive is given in Fig. 1. It is sometimes called a "double Mallet type" from its peculiar truck arrangement, but it has been properly christened the "Colonial type". Each driving axle is operated by a pair of motors, which are mounted rigidly on the frame of the locomotive, directly above the axle, and are geared to a quill surrounding the axle. The quill drive is exactly the same as shown for the 071 locomotive in Mr. Murray's paper, but there is only one gear required where two are necessary for the single large motor shown on the 071 locomotive. It is a strange thing that for single-phase work at any rate two motors of a certain total capacity can be made lighter and cheaper than a single large motor of the same capacity. We have therefore applied two small motors here, where on the 071 locomotive one motor is used. This design has the following advantages:

First. Coupling two small motors permanently in series gives the effect of a high voltage motor. This reduces the sizes of cables and control losses on the locomotive.

Second. Only one gear is required where two would be necessary with the single large motor developing the same tractive effort. Both pinions on the small motors drive the same gear. This reduces the weight very materially, and also the expense of installation.

Third. The small motors are much better adapted to the space between the wheels than a large motor, because the only way to increase the capacity of the motor is to increase its diameter, and when it becomes necessary to use twin gears for a large motor, the space available between the wheels for the motor itself is very much reduced, and consequently the diameter and weight must be greatly increased. It must be noted that the total number of running parts in the motors, *i.e.*, commutator bars, brushes, brush holders, poles, etc., are practically the same whether one motor is used or two. There will therefore be no more possibilities for trouble developing in the two motors than there are for one, and cost of repairing the small motor is very much less than making similar repairs on the large motor.

Fourth. The control equipment itself, on account of having a higher voltage, is simpler and cheaper.

The weight of the locomotive as shown is 116½ tons, and will develop continuously a tractive effort of 12,000 lbs. at 35 to 40 miles per hour. It will also be used for hauling heavy passenger trains up to speeds of 50 miles per hour. The weight as given includes the complete steam boiler, water tank, and direct current control equipment. With these parts removed, the weight would scarcely exceed 108 tons, showing that a very substantial gain has been made in the design of the single-phase electric locomotives, since the first ones were introduced. This machine will haul the heaviest train on the New Haven Railroad, whether it be a 1500-ton freight or an 800-ton passenger train, and will develop a good speed with either.

The mechanical design of the locomotive is also quite novel. The two middle pairs of drivers form a rigid wheel base, and an outer driver with its pony axle forms another rigid wheel base, which leads the locomotive. The deep plate frames are entirely outside of the axles, and are connected at the ends by heavy bumper girders, the bump being transmitted to them through the leading truck frame. The entire construction of the locomotive lends itself to lightness, as well as strength, and we expect to hear some excellent reports on the performance of this locomotive.

John W. Lieb, Jr.: Considerable has been said about the importance of power house operation in connection with the electrification of trunk line railroads, and I hope I may add a mite to the discussion in that particular direction. The power station companies, companies distributing light and power in our big cities, such as the companies in Chicago, New York, and similar communities, are, I need hardly say, desirous of getting that business. We are not very much interested in the question whether the roads operate at three-phase or single-phase, or by the direct-current system, provided we can get the current supply to them. That is selfish, I will admit, but it is also business, and it is in the line of the economical development of electric power. We would, however, urge on this question of standardization, that it is of immense importance to the companies embarking on this question, to be able to exchange current with the local large supply source, and therefore, I was much pleased with Mr. Murray's plea for 25-cycle generation, even in the case of alternating current systems.

Now, we who are engaged in the lighting and power distribution business believe that we can be of immense assistance in hastening this electrification problem, because one of the great difficulties is the immense investments that are required in accomplishing this electrification; but if the terminal companies and the railroad companies can feel that they can obtain their power supply at a cost certainly not to exceed what it would cost them, and save that enormous element of investment, which the local lighting and power companies are ready to supply, we believe that we have contributed at least one important element toward hastening this consummation.

I need hardly make a plea here for combination service, as between railway service and lighting and power service, but I will say this—that a careful study of the times of peak load between lighting and power systems shows the immense economical advantages which may accrue through a combination of these services, not only in the enormous saving of investment which will come even by so small a difference of maximum loads at peaks, of a difference in time of fifteen minutes between the railway and lighting peaks, which in the case of power plants of 100,000 kw. or more may represent a saving in investment of 1,000 or 1,500 kw., but also in the very greatly improved load factor which results from this diversity factor, and we all know what an important place the load factor has in the central station power cost economy.

Something has been said about storage batteries, and I would like to say a word as to that, and that is of the vital necessity which the storage battery is to-day in this question of absolutely certain continuity of service. I am frank to say that I believe our very large power systems, certainly those for the distribution of light and power, have a record for continuity of service which they would not have, and it would be practically impossible to maintain such a record, without the assistance of the storage battery.

It is true that the conditions of battery operation have greatly changed in the past few years. We have departed from the idea and necessity for using the battery for large current output, for continuous use, or the idea that in order to keep batteries in live condition they must be charged and discharged at minimum intervals, say once a week, or several times a month. We are satisfied now that we can obtain and maintain batteries in perfectly healthy condition by using them simply as a reserve, as an insurance, and for this purpose their value is simply inestimable. They play today an immense part in central station economy, and by having the railroads install their own batteries to assist in the distribution end especially, of course, with direct current, they will be able to bear with the local lighting companies the incidental economies and advantages which come from reducing peak demands.

I would like to make, therefore, an urgent plea for a settlement on this question of combined service, believing that, first, it will assist in the economical solution and hastening of this electrification problem, and secondly, because of the enormous advantages which will accrue to both the railway and lighting companies in the adoption of combined service.

In this particular field, I cannot hesitate for the moment it takes, to give the praise which should be due to this great institution, the Commonwealth Edison Company, in having been the leaders in this enormously important field, and having made practical demonstrations on a large scale of the advantages which were likely to accrue, and which do certainly accrue, from this combination of service.

Charles. F. Scott: I would like for a moment to compare the difference in the discussion of the railway question in the Institute a few years ago with the discussion to-day. At the Great Barrington meeting, held nine years ago, there were many railway papers presented, and many prominent engineers took part in the discussion of these papers. I have run through the proceedings of that meeting very carefully, and the one urgent question in the minds of all was this—How can we operate electric railways by supplying alternating current directly to the car or locomotive? And the solution which they thought apparently impossible was—"Where shall we get a motor? If we had a single phase alternating current motor the difficulty would be solved." A few months later was presented the paper proposing that motor. About five years later one of the most important railways in the country began operations under certain handicaps. The work was undertaken very quickly, the locomotives had to be designed and put in operation in a short time, there was not available the ten years which direct current had for its development, and they had the handicap of operating both by alternating current and direct current; nor was the motor the whole problem, for the line question, the switch question, and the generator question, came in as even more important than the motor in practical operation.

We have heard with great interest of very interesting tests which were made here in Chicago on switches, on a system on which short circuits were rare, where the high-tension circuits are protected in cables underground. On the New Haven system, with 100 miles of trolley wire in railway service, where short circuits were more or less frequent, with a generating capacity greater than in the tests here made, the solution had to be worked out while the railway was operating. That is one example of the kind of problems that come up in large work in a new field. Now we know that the alternating current will operate satisfactorily, and it is a choice between systems. The manufacturing companies have done their part, they put hundreds of thousands of dollars into this development. The problem has been crystallizing into a matter of operation. What are the operating conditions? What are the things which cannot be determined in the designing room or testing room of the manufacturing companies? The papers, such as are now presented, give records and facts which present to all the problem which must be worked out, jointly, by manufacturers, consulting engineers and railway men—what are the conditions of operation and how can they be met and by what system? Do we want to standardize? Yes, we want to standardize as rapidly as we are sure of our ground, but we want to leave open the opportunities for development. Several of these developments were suggested this morning—a mercury rectifier, the induction motor operating from single phase, and these, I believe, have been the only things looked forward to in the future. But these, as well as the single-phase motor, will all operate from the single-phase trolley, so that the single-phase system, as a general railway system leaves them open for adoption in the future. It is significant that Mr. Murray, who is in the best position to know the difficulties in operating a single-phase road, is the man who is loudest in its praise.

Frank J. Sprague: I have heard the few remarks made by Mr. Storer and also the statement by Mr. Murray. I have avoided all reference to overhead or third-rail matters in yards, advocating neither the one or the other in the brief remarks I have made. The overhead construction shown by Mr. Murray is equally applicable for direct current or single-phase current operation, so if that in his opinion is the determining feature, I am glad of it.

Mr. Storer intimated that in passing comments on Mr. Wood's paper I made some invidious comparison between the upkeep of the third-rail and the overhead structure on the West Jersey & Seashore road, and that I might have taken the trouble to speak of the local conditions. I do not know what the local conditions are. I took the paper and gave the relative costs of third-rail or overhead trolley upkeep simply as incidental facts.

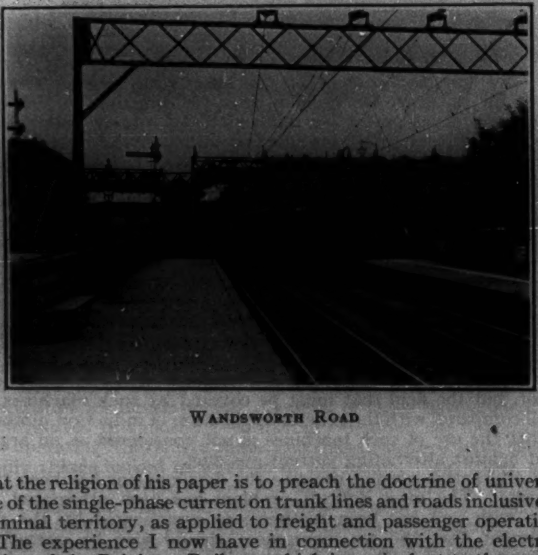
E. F. W. Alexanderson: There is one phase of the subject of trunk electrification to which I wish to call attention. Mr. Murray has referred to the same by making the statement that the system was laid out with the consideration in view that the traction work at some later time would be done by induction motors.

Whether it should be considered as unfortunate or not, it is a fact that the development of the alternating current motive power for railroad, has been in opposite direction to the corresponding development for industrial and mining enterprises. The alternating current distribution system is admittedly unrivaled and the use of the same is supported by the undisputed superiority of the induction motor for all purposes where such motors can be used. From the fundamental system of power supply by induction motors has grown up a number of special developments like the single phase induction motor, the single phase commutator motor, and the polyphase commutator motor. A campaign has been going on for several years for exploiting inventions along these lines, and to define the special requirement where an induction motor cannot be used to advantage in order to find application for special apparatus in order to meet those requirements. All those machines are expensive and objectionable in many ways compared with the induction motor, but the field that must be covered by such machines is small compared with the general application of induction motors, so that the use of such machines is not considered as an argument against alternating current systems.

In alternating current practice the development has been the opposite. The most difficult problem has been attempted to begin with and has been furthermore complicated by the requirement that the a-c. equipment should also be operative on direct current. The result is that the a-c. traction system has been largely discredited. If the development had been the opposite, if the three-phase induction motor had gained an established right in the railway field, if then the single-phase distribution had superseded the three-phase, yet maintaining the constant speed induction motor, and finally the commutator had been introduced for such special conditions of traction where the variable speed characteristics are valuable enough to warrant a higher expenditure, then the various problems of railroad electrification might have appeared in a quite different light.

In view of Mr. Murray's statement, it is gratifying to see that he has already considered the possibility that a development of the motive equipment might be started over again on a more sound basis. It might be premature to predict that all the traction work under Mr. Murray's supervision could be carried out by induction motors, but I feel confident that the larger part of it could, with a greatly reduced expenditure both in first cost of equipment and in maintenance.

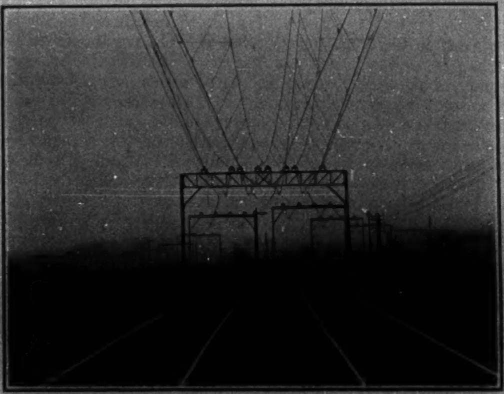
Philip Dawson (by letter): I entirely agree with the paragraph in the commencement of Mr. Murray's paper, in which he states that the religion of his paper is to preach the doctrine of universal use of the single-phase current on trunk lines and roads inclusive of terminal territory, as applied to freight and passenger operation.



WANDSWORTH ROAD

The experience I now have in connection with the electrification of the Brighton Railway which is equivalent to the equipment of over 60 miles of single track, (a large portion of which has been running since the beginning of 1909) has convinced me that there is now no longer any doubt that the single-phase system is at least as good as the continuous current system for operating suburban traffic requiring rapid acceleration, and with short distances between stopping places. This having been demonstrated by actual experience, there could be no doubt that for the electrification of any of the main line railways, the only system which could be considered is the single-phase one. No one I think denies that for long distance work the single phase is the only solution. The contention of those, who through thick and thin uphold the continuous current, is, that for short distance work the continuous current is far superior to alternating, and that therefore it should be used for this class of service, and that when long distance work becomes necessary, the single phase system should be installed in addition to it.

It may be interesting to know that we have had practically no troubles or serious inconvenience of any kind since we started service in 1909 and that with the multiple unit trains the average annual mileage per motor coach, including all our spares, and those which are being overhauled, was last year over 58,000 miles.



Leigham Junction

Our average speed with stations three-quarters of a mile apart, is 25 miles per hour. The line consists of nothing but curves and gradients and at the start, out of Victoria station, we have a gradient of one in 64 for over a quarter of a mile.

Besides this we have five sections where overhead conductors are connected to earth which thus seriously interfere with acceleration; one of these dead sections being just at the foot of the gradient out of Victoria station. Our average acceleration throughout the whole period of acceleration from 0 to about 35 miles an hour is one mile per hour per second.

We wished we could increase this by increasing the size of motors and the capacity of the power station; experience, however, has shown that the acceleration I originally selected is sufficient, and the increase in traffic since electrification started has been over 150 per cent and it is still increasing. This is a very important fact particularly if we consider that the South London line is intersected and paralleled by a very large number of electric tramways, that the saving in time is only about 10 minutes, and that the fares on the electric railways are nearly double those on the tramways.

Wandsworth Common

In connection with the experience which has been obtained with continuous current electric railways and single phase current electric railways, there is no one who has greater right to speak than Mr. Wittefeld, the Chief Engineer of the Prussian Government Railways. He has constructed and operated both continuous-current and single-phase railways. The continuous-current is one in Berlin going to Lichterfelde and worked by most up-to-date continuous-current apparatus and having very heavy suburban traffic. The single-phase line is that at Hamburg, both having now been worked for some years, and Mr. Wittefeld is the only engineer and railway official I know who has this dual experience at his disposal.

His letter addressed to me in connection with my paper before the Institute of Civil Engineers states:

"Your satisfactory experience regarding single-phase traction for working surburban lines, entirely agrees with ours on the Blanknese line. It can no longer be doubted, in accordance with my own personal experience, that for suburban electrification the single phase system is at least as good as the continuous current system. The experimental results for long distance traffic with very heavy as well as fast trains on the section Dessau Bitterfeld on this system have been most satisfactory. The large electric locomotives driven by connecting rods have surpassed all expectations. It is now my unshakable decision that the single phase system with the experience we have now gained, is the only system which can generally be used for electrification of main line railways. No experienced railway engineer, who wishes to be considered far sighted, can, I think, come to any other conclusion."

Besides the above, Dr. Wyssling, who was head of the Swiss Commission appointed to investigate the question of railway electrification, also wrote to me in connection with my paper. He said, "That according to his conclusions and that of his committee the single phase system is the one which is most suitable for heavy railway electrification, because the transmission and contact system is the simplest, because of the great variations in speed possible, and because it is the cheapest to install."

I am sending three views of the line which may be of interest.

W. N. Smith (by letter): As matters are now in the trunk line electrification field, installations upon a large scale are so few, that Mr. Murray is in the unique position of having had more practical experience than almost any other engineer in his special field—which gives him a distinct advantage over his critics, both past and present.

This installation in general is an illustration of the principle, that in any new departure the engineer can expect to learn a vast deal about structural and operative details as he goes along and at the same time can be confident of being generally upheld by results, in the decisions he had to make when planning the work.

It may be well to keep in the foreground Mr. Murray's definition of a trunk line. About a year ago, before the New York Railway Club, he defined his conception of a trunk line as "A line connecting large cities which are separated at some considerable distance. The portion of a trunk line which lies in the immediate vicinity and the outlying districts of those cities will carry upon it a suburban traffic."

Without criticising this conception, it might easily be implied from Mr. Murray's present paper that he considered as trunk lines only such roads as might be in the same class with the New Haven, namely, a main trunk of from two to four or six tracks, with numerous single and double track branches or net works and a heavy suburban service. It is a well known fact that some of the most important railroad lines connecting the large cities of the country are single track lines, particularly in the less densely settled portion of the country, though in some sections the most important roads are making progress in double tracking. Nevertheless, there are many roads that are not likely to double track for at least one more generation, and yet are, in the general opinion of themselves and the public, entitled to be called trunk lines, as is further borne out by the fact that all rolling equipment upon steam railroads, whether main lines, branches or otherwise, is interchangeable; and so far as structural considerations are concerned, trunk line conditions are usually conceived to include branches or side lines, whether located so as to be fit for electrification, or not; as well as the main arteries of traffic which have already reached or may ultimately reach that density of traffic which determines the economic suitability of electrification. The Spokane & Inland Empire Line, for instance, is more than 120 miles long and though it does not connect Spokane with any city even approaching Spokane in size, it is still fitted for handling standard trunk line equipment and actually does handle railroad freight trains of a respectable size with the system of electrification advocated by Mr. Murray, though at lower trolley voltage. Its peculiar situation, as respects cost of providing power for operating, is said to have favored the adoption of electric motive power, as distinct from considerations of traffic density, thus making it a special case. It would not be called a main trunk line, for instance, in comparison with the Northern Pacific; but the adoption of that equipment which is most suitable for long lines with heavy trains brings it into the trunk line class, so far as electrification is concerned.

To summarize, it seems to me that the accomplishment of trunk line electrification is broadly determined, first of all, by the general characteristics of railroad rolling stock used for transportation, and in a secondary degree by geographical location.

Mr. Murray states that the criterion of financial return is "how much it costs to produce the necessary tractive effort" in the several types of locomotive mentioned. The writer believes that this statement of the problem, while it appeals to one's engineering sense as probably true, is still so vague as not to carry conviction. Rightly or wrongly, the ton-mile or the car-mile are the units most commonly used for comparing transportation performances—as is well shown by Mr. Murray's own data. It seems to me that until some new unit is invented which will more correctly express the desired relationships, the ton-mile or car-mile should be used as explicitly as possible in making such comparisons. Annual reports of the largest steam railroad systems commonly include a great deal of statistical information that is or can be referred to a ton-mile basis for comparison, and the present Interstate Commerce classification enables the compilation of a good deal of interesting information regarding the various costs of train performances per ton-mile, if one will take the trouble to dig it out of a comprehensive report.

I am impressed with the magnificent performance of the New Haven system as regards the small amount of train delays; but it should not be forgotten that this particular system has four tracks and an arrangement of feeder section switches on the anchor bridges which enables sections to be readily isolated in case of trouble, thus preventing many delays providing the trouble is discovered soon enough. It is very doubtful whether any single track line with an equivalent train mileage per mile of single track could exhibit such a clean record, as the difficulty of reaching and remedying trouble without interfering with train service on a single track is vastly greater than on a 4-track system. The high grade insulation which Mr. Murray advises to be used as the cheapest means of securing satisfactory trunk line operation, is even more necessary on a single track than on a 4-track trunk line; and this is as true of strain insulators as of the straight line insulators. Mechanical sufficiency in every part is equally important for the same reason, and the various details mentioned by Mr. Murray as constituting distinct mechanical improvements, should therefore be all the more carefully followed in single track line construction.

Referring to Mr. Murray's remarks on storage batteries for trunk line electrification, he is undoubtedly correct for trunk line electrifications approaching the magnitude of the New Haven Railroad. But cases have arisen in the past, and probably will from time to time in the near future, where the use of a storage battery offers some economic advantages. Here, again, the Spokane & Inland Railway furnishes an example of trunk line electrification under special conditions which made a battery adjunct advisable, even with the extra conversion losses from continuous back to alternating current when discharging. The fact that the current for this system is generated by water power will go far to explain the reason for the adoption of the battery in this instance.

In view of the numerous failures of the early types of storage battery in street car service during the early development of electric traction, it may at first appear idle to some, to even consider the possibilities of the storage battery for direct propulsion of cars in trunk line work, but the gradual improvement in reliability that the lead battery has developed in electric vehicle service; the development of the nickel-iron-potash battery by Mr. Edison; and the successful application of both these batteries to light railway work during the past year, in New York City, Philadelphia and Washington, together with the successful experiments in the operation of branch lines of the Long Island Railroad and the Erie Railroad, each of which now has a battery car in operation, all indicate that we are not yet at the end of our resources as to the choice of an electric propulsion system for at least some types of steam railroad service. The developments of the past year have been on a small scale, but are most encouraging, and indicate that if both electric tramway and steam railroad engineers are willing to reconsider their previous conceptions as to design and weight of car bodies, anti-friction journal bearings, motor capacities, gear drives, and battery maintenance, in connection with the possibilities which battery car propulsion offers in the production or purchase of electric power at a high load factor, (which minimizes power-station or sub-station investment and operating expense, or enables the purchase of off-peak power at minimum rates), they will be enabled to view the economics of heavy electric traction from a new angle.

This applies more especially at the present time to electric trunk-line branch service; the next step will be in the direction of battery traction for suburban service at moderate speeds.

The more recent successes of storage battery traction have been largely due to the fact that the cars thus far constructed have been practically built around the battery, and are of very light construction, with anti-friction bearings, thus reducing both the tons to be transported and the pounds per ton resistance of the car journals. The writer believes that the problems to be solved in connection with the development of storage battery traction for trunk line branch and suburban service are much more of a mechanical nature than electrical, and reduce ultimately to the question of how light it will be possible to construct a car, suitable for operation on steam railroad tracks, that shall be regarded as sufficiently strong to insure its own stability and the safety of the passengers against all shocks that can reasonably be expected, and can carry enough battery for economical operation in the service it is desired to handle.

These questions will be settled by the judgment of railroad mechanical experts and will doubtless require much experimental working out; nevertheless, I believe that the field for exercise of ingenuity in this line will be cultivated, though it may be a few years before it has acquired the status now enjoyed by the several typical systems involving working conductors. The fact that power in any necessary quantity can now be purchased at the lowest possible rates for charging battery cars during those periods of the twenty-four hours when they are most likely to be idle, together with the entire abolition of working conductors for the tracks, which eliminates the question of interchangeability of different working conductor systems, constitute arguments that will be likely to appeal to steam railroad men. Such possibilities are, of course, predicated upon the assumption that the storage battery of the future will prove to be as reliable and subject to no more depreciation per car mile than modern types of motors and generators. Should this development eventually come into being, and should steam railroad officers permit themselves to utilize lighter car bodies, we will then have available one more method for utilizing electrical apparatus to supersede the steam locomotive, in some situations, at a lower first cost than is possible with the present systems of instantaneous transmission of railway power.

Railroad electrification is at the present time much desired by the public at more than one large terminal. Whatever system of electrification be followed, the probability is that the suburban service of almost any railroad would be the first to be electrified, thus resulting for a time in a mixed steam and electric system. The initial electrical equipment must, therefore, operate in some degree interchangeably with the existing steam equipment, and all the circumstances surrounding steam operation must be given consideration as affecting the first cost, operation, and general durability of the proposed electrical equipment.

Mr. Murray has fulfilled the engineer's function of getting superlatively good results under certain difficult conditions with the electrical apparatus now available for such work. I must confess, however, to a degree of caution when it comes to declaring the state of the art at this time as so complete, that all work in the immediate future should be based upon present practice, even on the remarkable showing made by the New Haven Railroad installation. I shall not be surprised if, by the time that railroads in general are able to pay for electrification on a large scale, some methods less costly, both as to investment and daily operation, will have been devised for accomplishing the desired results, especially in those terminal situations where the need for steam railroad electrification is now most pressing.

B. F. Wood: In view of the limited time at my disposal I shall confine my remarks to the suggestion made by Mr. Lieb that power should be purchased from power companies rather than generated by the railroad companies at their own plants.

By reference to the table showing Cost of Construction it will be noted that the investment in power station and transmission line is nearly a quarter of a million dollars. With this amount included the net earnings during the year 1910 were sufficient to make a return on the total investment for electrification of about 8¼ per cent. If power could have been purchased at rates prevailing in Chicago for such service, the same net earnings would have shown a return of nearly 9¼ per cent on the lesser investment necessary; showing conclusively that the power station is not earning the average rate of return.

At the time of the electrification of the West Jersey & Seashore Railroad it was not possible to purchase power for such operation and it was therefore necessary for the railroad company to build its own power station.

Again, the rates for power in some cases have not been based upon the cost of furnishing the service but have been fixed with relationship to the charges for other service differing in character and in a good many cases such rates have been prohibitive.

The responsibility, therefore, for the railroad companies building power stations rests largely with the power companies and if they are to take over this business they must fix their rates on a basis that will give a return on investment necessary for such service and not on the average cost of power.

C. P. Steinmetz (by letter): Mr. Murray's paper appears to me very interesting and valuable for the complete information which it gives on the practical experience of a number of years operation of a section of a trunk line railway, electrified by the single phase alternating current system.

Especially important appears to me the conclusion which Mr. Murray reached as the result of actual experience of several years successful operation, that 25 cycles is the proper frequency for railway electrification. This entirely agrees with my opinion, which I expressed here at a previous occasion some years ago: "If the single-phase commutator motor can not be designed and operated at 25 cycles, it can have no future and no right of existence." No odd frequency, as 15 cycles, or 8 cycles, can be seriously considered, especially after the unfortunate previous experience. In some special instance, a railway section isolated from all sources of electric power supply, some odd frequency as 15 cycles may appear to have some advantage without any immediate disadvantage, just as 40 cycles appeared advantageous for mill work; but sooner or later the disadvantage of the odd frequency will become apparent, and it would be fortunate if then it would only mean scrapping the odd equipment, as is being done in Southern 40-cycle cotton mills, and if the odd frequency has not spread so as to be irredeemable, as 50 cycles in Southern California and 40 cycles in the upper Hudson River development.

John B. Taylor (by letter): Under the heading of Power House, Mr. Murray points out the advantages of employing three-phase generators rather than single phase, even though the bulk of the energy is supplied to a single phase trolley system. This naturally results in unbalanced voltage which is a point of greater or less importance depending on the amount and fluctuations of the unbalancing, as well as on the types and relative capacities of the pieces of apparatus connected to the three-phase system. In general, polyphase machinery, such as induction motors, synchronous motors and rotary converters, connected to an unbalanced system, will to some extent improve the balance at their own expense, so that such pieces of machinery must have their rating changed or the amount of heating will be greater than the heating would be for the same output on a normal balanced system. How serious this curtailing of rating or increase of heating will be, is, of course, a matter dependent on the particular conditions prevailing on the particular system under consideration. Bearing on this point, Mr. Murray makes one statement that seems open to question: ". . . such (unbalanced voltage) as remains is easily compensated for by arrangement of transformer taps in the substations reducing the three-phase current from high to low voltage for motor or synchronous converter application." While it is a well recognized proposition that any polyphase system can by suitable transformer connections be converted to any other polyphase system, it is not evident that the mere placing of taps on transformers will convert an unbalanced three-phase system into a balanced three-phase system, since any differences in the voltages must be accompanied by changes of phase relation. While suitable transformer taps may be selected so that the voltage from each individual transformer can be given a desired value, these three voltages cannot be interconnected to form a typical three-phase system, on account of the distorted phase relation. It is of course possible to obtain both the desired voltage correction and desired phase relation by the general principles of phase transformation, that is, connecting in series two or more windings having different phase relations. Such interconnection of phases naturally involves specially constructed transformers and some complication of wiring to obtain the desired result, which cannot be accomplished by transformer taps alone.

R. E. Hellmund (by letter): There are a few statements in Mr. Alexanderson's paper which, while perfectly correct, might be misleading to the casual reader of the paper. Mr. Alexanderson states " The output of the converter must be substantially one-half of the polyphase capacity of the motor." He also says " The single phase capacity of the converter corresponds to the input of one phase of the motor, or one-half of the total output."

The following statement, which is also correct, might give to some readers, a better idea about the size of the converter—" The polyphase capacity of the converter is exactly the same as the polyphase capacity of the motor." In other words, if the two machines would have the same speeds, they would have to be exactly the same size.

In comparing the phase converter with the motor-generator set, Mr. Alexanderson seems to favor the phase converter somewhat. The generator of a motor-generator set is a polyphase machine and its size would, therefore, be the same as that of the phase converter. The driving motor being single phase would be about 40 per cent larger. Even considering that a motor generator set requires an exciter and that the converter is a squirrel cage machine, I believe that while a comparative weight of 1 to 4.5 may be obtained under special condition, a ratio of 1 to 3 or 1 to 3.5 would be more correct in the average case.

Mr. Alexanderson's statement that the converter will add only 26½ to 30 per cent to the weight of the motor, of course, is correct under certain assumptions. This question depends, however, entirely upon the possible relative speeds of the motor and the converter. The saving accomplished by the fact that the converter is not a driving machine, is probably not very large in most industrial applications. It is my experience, that the electromagnetic stresses during the starting period of induction machines is usually the governing feature and will not permit a light mechanical structure, except in case of a very large air gap, which in turn, would spoil the power factor. Nevertheless, the system has certain advantages and its application will be well worth considering in some cases. While no mention of the possibility of using the system for railway work has been made in the paper, this question might be of interest. Since the converter adds 25 to 50 per cent to the motor weight, the total equipment will be as heavy or heavier than the straight single phase commutator motor equipment.

The possible omission of the transformer on the locomotive, which is one of the main advantages of the straight three-phase operation, will, in most cases, not be possible with the proposed phase converter because the equivalent single-phase line voltage would have to be considerably larger. In fact, it is liable to pass the voltage limit for which the converter and the motors could be safely and economically insulated. A transformer on the locomotive will, therefore, be required in the majority of applications.

The application of the system for general railway work seems, therefore, not very advisable, since the introduction of an intermediate revolving machine would reduce the reliability and since the constant speed feature of the induction motor is a disadvantage in general railway work in this country.

In such cases, however, in which three-phase operation is desirable for some reason or other, the proposed system might be considered. Especially in cases where the distances are large, while the number of locomotives is small, some saving in first cost over the straight three-phase system, might be accomplished.

While the rolling equipment will be, of course, considerably heavier as well as more expensive than the straight three-phase equipment, the saving made by the cheaper overhead construction may possibly more than offset this disadvantage in some cases.

In connection with railway work, I would like to bring up the question of regeneration and ask whether this point has been investigated to any extent. It might also be well to ask the question as to what would happen if the power should be off for a short interval of time, which would permit the phase converter to reduce its speed to any extent. It seems that in such a case, there is danger of the phase converter falling out of speed, especially if it is designed for as high an efficiency as Mr. Alexanderson proposes.

While it is quite possible to obtain a good efficiency with a phase converter, it seems rather difficult to obtain at the same time, good starting conditions for the same, as well as a strong tendency to pull back into speed whenever the power goes off.

In regard to the power factor, it might be said that the total power factor probably would be rather low in spite of the fact that the power factor of the converter may be as high as 95. If we assume for instance a motor with a power factor of 90 and a phase converter with a power factor of 95, we obtain a combined power factor of only 77.5. The same combination at half load would have a power factor of 45 to 50. This is about the most favorable condition which may be obtained. In many cases, especially in case of the lower speed of a two speed motor, the power factor may come as low as 60 or even lower at full load.

In fact the power factor conditions for the phase converter system are very much the same as for two induction motors operating in cascade connection in so far as two machines have to be magnetized. A comparatively low power factor will, therefore, be inherent to the system. Special means for correcting the power factor would further complicate the system, so as to make their use hardly worth while considering in connection with railway work.

E. F. Alexanderson (by letter): In answer to the questions brought up by Mr. Hellmund regarding the system of single-phase operation with phase converters and polyphase motors, it can be stated in general that the system is applicable for regenerative breaking in the same way as the three phase system, and that it has been demonstrated that the phase converter has no tendency for falling out of step if the power is interrupted. As soon as the power circuit is broken all the magnetic fields disappear and the phase converter continues to run light, being retarded only by friction and windage. It therefore would take a considerable time for it to slow down to any great extent. However, it was demonstrated that the speed might drop to $\frac{1}{3}$ of full speed, and yet the phase converter would come up to full speed as soon as the circuit was re-established.

The figures given in the paper regarding the relative weight of motors and phase converters are of course in no way to be considered as general—they refer to a specific case of locomotive equipment, which appears to be particularly suited for heavy mountain railway work. Any comparison between the phase converter system and the single phase commutator motors must therefore be considered from this point of view. It can be stated in the case that has been studied that the phase converter system gives a much lower weight of locomotive than the single phase commutator motor. The controlling feature is not so much the relative weight of the auxiliary apparatus as the space factor of the motor itself, which determines the type of locomotive which may be used.

Regarding power characteristics the indications are that the average power factor will be as good as or better than the corresponding single phase commutator motor.

Edwin B. Katte (by letter): The contribution to the discussion of Mr. Murray's paper which I have to offer is based upon some direct current experience, and in order to avoid the impression that I favor direct current to the exclusion of all other systems for trunk line electrification, I will preface my remarks by saying that I believe any steam railroad can be equipped for reliable electric operation with either of the three commonly discussed systems; but that one of these systems will more satisfactorily meet the special conditions of each case, and that at the present time no one system of electrification has been developed to satisfactorily meet all the conditions of every trunk line problem.

It is not a question of direct-current, single-phase or three-phase alternating-current that we should be discussing, but rather steam *versus* electric operation, and until we do confine ourselves to the real issue and can show economy in electric operation, we cannot expect to interest steam railroad men as a whole.

Electrification has proved itself entirely reliable on many steam railroads and in some cases has demonstrated a saving in operating expense. However, I do not know of a single instance in which it has been shown that this saving is sufficient to cover the additional fixed charges, and I hazard the opinion that no trunk line electrification will prove economical as compared with steam until an entire steam locomotive division has been electrically equipped.

Electricity, at the present time, must be considered as more or less of a luxury or as a means to some end other than economy of operation. The great trunk line terminals in New York City would not have been possible were it not for electricity, and the operation of the Detroit River and the Sarnia tunnels would scarcely be safe were it not for electric locomotives; in such cases as these the high cost of electricity is justified. But on the other hand, if a city or other property, through which a steam railroad passes, is to be improved by the elimination of the nuisance of steam locomotives, the cost of this property improvement should be shared in by the city, state or individual in a manner similar to the present practice in the matter of grade crossing eliminations.

With much interest have I read Mr. Murray's statement, to the effect that " we have made electrification in its various forms work, we can now make it pay," and although I have carefully perused every page of his paper, I have failed to find the last statement justified, except in his claim that—" to make electrification pay, he (the electrical man) must be able to reproduce the four classes of steam tractive efforts by electricity, with a total investment, the interest on which must be carried by the economy to be effected over steam operation." Then follow data about water consumed per ton-mile of steam trains and watt-hours per ton-mile for electric trains, concerning which you are all more or less familiar, but not a word regarding the relative cost per ton-mile of steam and electric trains in similar service. It is this cost data in which we are so vitally interested, and this I had hoped to find in Mr. Murray's analysis. Here I may add that cost figures for comparative performance on the New York Central system are not available for the reason that the service is still mixed steam and electric; steam locomotives operate over electrified tracks and multiple-unit trains are hauled a large portion of their run by steam locomotives due to the still uncompleted condition of the Electric Division.

In Fig. 38 Mr. Murray has reproduced several speed-time curves for single-phase locomotive runs and has computed the current consumption in watt-hours per ton-mile for local and express service on the New Haven Railroad. A comparison of current economy based upon watt-hours per ton-mile for different systems on different railroads is not very conclusive because of the effect of grades, curves, station stops, schedule speed, etc., but as an indication of what might be expected in comparing direct-current and single-phase locomotives in the same service, I have selected locomotive runs on the New York Central direct-current system as nearly the same as those given by Mr. Murray as the train schedule will permit, and the results are tabulated below:

LOCAL TRAIN SERVICE

Items	Single-phase loco.		Direct current loco.	
Direction of run	W. bound	E. bound	N. bound	S. bound
Average grade	+0.053%	-0.053%	+0.129%	—0.129%
Train number	213	216	333	1016
Date	2/11/11	2/11/11	6/6/11	5/31/11
Run between	Stamford-Woodlawn		G. C. Term.-No. W. Plains.	
Train weight, tons	316	285	266	250
Length of run, miles	20.6	20.6	23.9	23.9
Time of run, min	55.8	55.8	61.8	62.8
Schedule speed miles per hr	22.1	22.1	23.2	22.8
Number of stops	13	14	20	18
Stops per mile	0.63	0.68	0.84	0.75
Watt-hr. per ton-mile	85.4	74.2	81.6	59.4

EXPRESS TRAIN SERVICE

Items	Single-phase loco.		Direct current loco.	
Direction of run	W. bound	E. bound	N. bound	S. bound
Average grade	+0.053%	-0.053%	+0.129%	—0.129%
Train number	9	16	1005	1004
Date	2/11/11	2/11/11	5/9/11	5/29/11
Run between	Stamford-Woodlawn		M. Haven Jct.-White Pls.	
Train weight, tons	477	493	432	434
Length of run, miles	20.6	20.6	17.11	17.11
Time of run, min	27.6	25.2	23.3	23.4
Schedule speed, miles per hr	44.7	49.0	44.1	43.9
Number of stops	0	0	0	0
Watt hr. per ton-mile	35.0	30.0	29.2	17.6

From the tables it will be noted that the trains selected for comparison are quite similar in weight, schedule speed, number of stops, etc., for each class of service, however there is some difference in the grade of the two railroads, the New Haven having an average descending grade of 0.053 of one per cent from Woodlawn to Stamford, and the New York Central an average ascending grade of 0.129 of one per cent from Grand Central Terminal to North White Plains. For this reason the comparison is made of trains operating in both directions and in all cases, both for express and local trains up or down the grades, the saving in current consumption is in favor of the direct current locomotive.

COMPARISON—ELECTRIC OPERATION
NEW HAVEN R.R. AND NEW YORK CENTRAL R.R. CO.
TRAIN MINUTE DELAYS PER MONTH

Month	New Haven R.R. Co.				New York Central R.R. Co.				
	Power houses	Trans. lines	Elec. loco.	Total	Power houses	Line S. S. 3d R.	Elec. loco.	Total	Loco. miles
1908									
July.......	0	2100	1183	3283	0	10	30	40	86922
Aug.......	132	1642	407	2181	0	33	45	78	89670
Sept.......	0	942	224	1166	0	0	18	18	89324
Oct........	0	2140	343	2483	0	42	30	72	89561
Nov.......	139	103	405	647	0	0	7	7	83822
Dec........	179	194	240	613	0	0	35	35	89738
Total......	450	7121	2802	10373	0	85	165	250	529037
Average per month...	75	1187	467	1729	0	14	28	42	88173
1909									
July.......	0	170	153	323	0	10	45	55	95482
Aug.......	0	548	97	645	0	54	154	208	91160
Sept.......	0	0	219	219	0	7	86	93	93688
Oct........	54	204	124	382	0	0	6	6	94893
Nov.......	0	42	96	137	0	18	27	45	89504
Dec........	0	55	315	370	0	8	12	20	91082
Total......	54	1019	1003	2076	0	97	330	427	555809
Average per month...	9	170	167	346	0	17	55	71	92635

SUMMARY

Total Train Minute Delays for Six Months.

New Haven R.R. Co....................................	1908—10373	1909—2076
New York Central Co....................................	" — 250	" — 427

N. Y. C. increase was due to an epidemic of defective fuses on locomotives. Of the 427 minutes delay, 234 were due to defective fuses.

There is no data given by Mr. Murray for converting the watt-hours per ton-mile into dollars and cents to cover all fixed and operating expenses for the entire electric service, and therefore the relative cost of steam and electric operation cannot be determined, and while there may be a saving in operating expense it is not known whether or not it is sufficient to cover the additional fixed charges incurred by the electrical installation.

The statistical record of single-phase operation gives ample proof of the improved conditions of that system; the reduction in train minute delays for the last six months in 1908, namely from 10373 to 2076, in the same months of the following year, is considerable. On the New York Central Electric Division, the train minute delays due to electric trouble for the same period in 1908 was 250 minutes and in the following year 427 minutes, of which 234 minutes delay were caused by an epidemic of defective ribbon fuses which were responsible for more than one-half of the delays before they could all be removed from the electric locomotives.

Mr. Murray points with justifiable pride to the single-phase locomotive performance of 15,700 miles per one locomotive failure. A similar good record has been made by the direct current locomotives, as shown in the New York Central record for March, 1911, of 26,655 miles per one engine failure; the total electric locomotive miles for that month was 106,622.

Again Mr. Murray refers to the single-phase electric locomotive record for reliability, and states that in November, 1909, there were 66,000 locomotive miles performed with but three minutes delay and informs us that upon such ground his Board of Directors stood in ratifying the single-phase system. A better monthly record has been made by the direct current locomotives on the New York Central system, the exact mileage being 101,765 made in April last, the single train detention being of four minutes duration, caused by a broken draw bar knuckle which contained a hidden flaw in the casting. Last month, that is May, 1911, the locomotives performed an average mileage of 112,893 per one train detention of five minutes caused by a defective air brake hose.

Little is said in the paper of the power station for supplying a single-phase system and nothing about its cost of operation; the storage battery is dismissed as a thing of the past, yet both have a very direct bearing on the cost of generating current, which after all is the main source of economy—or expense—in any electric traction system. It is well known that to generate current on unbalanced phases is more costly than on an equally loaded three-phase system; and aside from the insurance feature of batteries, their economical effect in equalizing the load on power stations has frequently been demonstrated. This has again been evidenced in the low cost of generating current at the Port Morris power station of the New York Central Company, where for some time the average cost to generate current has been about one-half cent per kilowatt-hour with coal costing approximately $3.00 per ton. It would be an interesting comparison if Mr. Murray would tell you what it is costing to generate current at the Cos Cob power station for the single-phase system.

It is encouraging to note that the many electrical and mechanical changes in the original New Haven locomotives, which Mr. Murray described in his former paper, have resulted in more reliable operation; this, however, should not be the only index of satisfactory results. The successful electric locomotive should not only be reliable but its maintenance in such condition must be at a low cost. The inspection, repairs, renewals and other maintenance of the New York Central electric locomotives during the first four years of operation have averaged between three and three and a half cents per locomotive-mile for all classes of service. It would be interesting if Mr. Murray would publish similar maintenance costs for the New Haven locomotives.

There is much in the paper concerning the additional weight of the New Haven Company's single-phase direct current equipment. This feature has been criticized before now by some engineers who have wondered—in the light of the knowledge that direct current would have to be used by the New Haven Company for a considerable portion of its mileage—why such a complicated and heavy equipment was ever adopted. No figures were then available to prove that it was more economical or reliable than the lighter and less complicated direct current apparatus, and none have yet been produced.

The figures given for the first cost of the single-phase trunk line electrification system are so very general in character and the range between the high and low estimates so great that no comparison can be made with the cost of the direct current system. However, the impression derived from the unit costs given is that the direct current system would be considerably less expensive, and this impression is in a way substantiated by a comparison of the estimates submitted last Fall to the Joint Metropolitan Committee in Boston by the New Haven Company for single-phase and by the New York Central Company for direct current electrification, wherein the average cost for single-phase electrification was $71,000 and for direct current $59,000 per mile, including all items entering into the first cost of the change of motive power.

Mr. Murray's final remarks are not to my mind conclusive; he states that his paper is not an argument for the single-phase system, that statistical records of first cost and operating expense make such a course unnecessary. No such records of first cost or of operating expense have ever, to my knowledge, been given to the engineering public, and such meager results as are recorded in his paper pertain to but 85 single-track miles of main line now in single-phase operation on the New Haven Railroad between Woodlawn and Stamford, while on the other hand, more reliable operation is to be found over the 126 miles of main line on the New York Central Railroad Company's direct-current system.

My purpose is not to argue the adoption of the direct-current system as opposed to the single-phase system, but to point out as forcibly as I may that the direct-current system has thus far made a better record than the single-phase, and therefore at least two systems of electrification are available for successful trunk line operation, and to urge electrical engineers to strive to prove the advantages and economy of electricity over steam as a motive power and leave the selection of the system to be determined by the requirements of each specific case.

H. Graftio (by letter): Although the New York, New Haven & Hartford Road's present electrification was proved to be a complete success, I cannot agree with Mr. Murray's conclusion and doctrine of the universal use of the single-phase system on trunk lines.

In my opinion one cannot possibly avoid the question of relative costs and merits of electrification by various systems (in hand and to come) for various specific conditions of the lines themselves and of the traffic to be handled on them, and one cannot substitute these very complex questions by the motto: "As electrification of trunk lines is now practically at hand, what is the correct system for all?"

"No system yet at hand is the correct system for all" would be in my opinion the only possible answer to the question, unless one be satisfied with very poor average.

And as regards the recommendation of the single-phase system, among others in hand, (which also proved to be very successful in the respective cases where they are used) to be the universal system, it would really mean too heavy a sacrifice for the numerous cases of trunk line electrification, where *we really can expect* now to see electric traction advantageously substituted for the existing steam traction.

I am by no means adverse to the single-phase system, or an advocate of some other system, but I do consider that one cannot forget the results obtained, for instance, in the recent Pennsylvania electrification with the direct-current system, or the really wonderful performance of the three-phase system used on the Italian lines and among them on the Genova Busalla trunk line.

It seems to me that the whole confusion in the so much talked of question of one single universal system of electric traction for trunk lines is the outcome of one fundamental deviation in pure logics. One very often refers the idea of electrification to entire systems of trunk railroads. So far and while one is reasoning in this general and abstract way, one might be perfectly justified in advocating some single universal system, and it is possible that the single-phase system might be, so far as we stand now, the best suited for such a general purpose, or might not be.

We have had the occasion to hear this same reasoning expressed by some of the reporters at the International Railway Congress held at Bern in July 1910, and so far as the hypothetical case was considered, these reporters were perhaps in some way justified. But the same reporters on the basis of very complete studies of electrification done for Bavaria, for Austria and for

Switzerland, informed us that the electric traction is in such a state as to advantageously supplant the steam traction on trunk lines in two cases, *viz.*:

1. If the cost of energy be less than so many pfennigs or hellers per kw-hr.

2. If the density of traffic has surpassed such and such limits.

Considering the cases mentioned, we see that even for Bavaria and for Austria (and for Switzerland too), whose representatives were precisely the reporters mentioned, practically only two categories of trunk lines *can stand* electrification versus the existing steam traction at all, and those are: mountain divisions of trunk roads sometimes connected with a few short flat divisions adjacent to these mountain divisions and with cheap sources of energy in the vicinity, or suburban sections of trunk roads adjoining large cities with a sufficiently dense traffic on them.

And precisely for these special cases of real practical possibilities of electrification, other systems, such as the three-phase and the direct current come out as more economical and more suitable for purely technical reasons than the single-phase system. This has and can be easily demonstrated by figures for each of these two special cases.

What remains then of the electrification of entire systems of trunk railroads, advocated as the chief argument for the selection of one unique system of electric traction? Nothing. And what is the weight then of considering a unique and universal system of electric traction? Nil; unless speaking of phantoms and dreams, because we cannot underestimate the present Queen of our trunk railroads—the modern steam locomotive, which is and will remain for a long time to come the cheapest and the best suited for innumerable kilometres of our existing railroads, and because we also cannot overlook results obtained by other systems of electric traction.

On the other hand we are progressing so rapidly in the art that nobody can pledge for ten years in advance that some other system will not come forward in the meantime, which would make competition for any of the existing systems hard.

Extrapolation has been always condemned by mathematicians, and in the case of electrification of entire trunk systems, or even lines, where millions are to be spent and where the directors of a railroad company, or the respective governments may ask for some specific explanation as to the return each year of a percentage on some of the money spent, it seems that engineers must be even more careful in this respect than mathematicians.

Let me remark also that, with the exception of motor car trains suited for local traffic, in the long distance service where heavy trains will have to be hauled by powerful electric locomotives, it really will not take more time or give more trouble to replace, at the respective junction stations, a single-phase locomotive by a three-phase one, for instance, or *vice versa*, than is being taken now in changing one steam locomotive for another.

The verv small complications in the distribution system, that may come out of this (or may not), are not worth mentioning now and cannot seriously be taken into consideration as a reason to overlook much more serious circumstances, such as economy and technical suitability.

The conclusions reached at the Bern Congress on the question of "systems" of electric traction seem to confirm in the fullest way the above opinion.

Clause No. 2, of the conclusions of the Bern Congress, accepted by the immense majority of the railroad men and electricians of all countries, both of Europe and of America, that were present and participated in the discussions, says: "There are various systems at hand and the selection of one or another system is dependent on its respective suitability in each case."

So better let now each system develop and fight for its own, as before, in finding more and more of the convenient field for its respective development. The fittest will win.

Gisbert Kapp (by letter): Mr. Murray has done good service to the cause of electrical engineering generally in showing that electrical working of main lines is perfectly reliable. Apart from the satisfaction which every engineer will feel at the success recorded in the paper there are two broad conclusions to be drawn from it. One is the importance of treating electrification not piecemeal, but as one organic and comprehensive change and the other is the importance of standardization. The electrifications carried out hitherto in Europe were mostly tentative and piecemeal work. Under these circumstances the fixed charges on powerhouse and lines and the low load factor of the powerhouse must seriously hamper the economic advantages which can be obtained if the working is extended to all classes of traffic including yard work. Mr. Murray's paper brings out the economical advantage of treating electrification as a matter of general and not partial application. This is also the experience in Europe where not only passenger, but also goods traffic is worked electrically, though the extension of electric working to yards has not been carried out so fully as on Mr. Murray's lines. The tendency is however that way also here.

The other broad conclusion, namely the desirability of standardization, is also fully recognized in Europe, but when we come to details we get onto debatable ground. Five years ago the Swiss Government called together a committee to study this question, but although reports were issued there is at present no such thing as standard practice in European railway electrification. Of the three postulates in Mr. Murray's religion, namely type of current, pressure and frequency, only the first may be considered as a standard with us. It is true that the Italian Government has adopted three-phase current for some portions of main lines, but there were special reasons for this decision and the Italian Government engineers have by no means closed the door on the single-phase system. Mr. Verola, the chief engineer to the Railway Department, stated in a letter to me that it is highly probable that other lines will be electrified single-phase. All the new main lines electrified or to be electrified on the Continent are on the single-phase system and the two examples of main line working we have in England are also running very satisfactorily on this system. We may therefore take it that Mr. Murray's suggestion as to type of current will be readily adopted, but if we come to the questions of pressure and frequency we find the most bewildering variety in present practice. In England and Prussia most lines are worked at 25 cycles, while Italy and the Duchy of Baden have adopted 15 cycles as a standard. The Swiss committee have also recommended this frequency as a standard. One of the reasons why Switzerland has adopted a 15 cycle standard with a 10 per cent latitude up and down is that the existing hydroelectric works have generally frequencies between 40 and 50 and by installing a frequency transformer of 3 to 1 ratio they could utilize their spare power for railway supply. As both Switzerland and Italy are water power countries and as the capital outlay for hydroelectric works is much heavier than for steam driven stations it is a matter of great economic importance to utilize the existing plants to the fullest possible extent and for this reason it seems unlikely that the standard of 15 will be abandoned for one of 25.

As regards pressure we have in Europe also a great variety, including all voltages from 2,000 up to 20,000, but the tendency of new lines is to adopt a pressure in the neighborhood of 10,000 volts. This is not so very different from Mr. Murray's suggestion that one need abandon the idea of coming to an understanding. Mr. Murray has shown that a pressure of 11,000 volts can be safely employed and there is nothing to prevent this standard being adopted also in Europe.

As regards the design of motors the question whether the frequency shall be 15 or 25 is not of paramount importance. Mr. Eichberg (whose motors are made by the Allgemeine) favors 25, while other firms, notably Siemens-Schuckert, favor 15, but there is no scientific reason which should make it impossible to design any type of motor for either frequency. As Mr. Murray has shown by his practical success that the frequency of 25 is possible there does not seem to be any very pressing reason to abandon it. The argument that some types of motor can be built a little more conveniently for the lower frequency can hardly be considered to weigh very heavily in comparison with the practical success which has been achieved with the higher frequency.

Discussion at Toronto

N. W. Storer: As Mr. Murray has kindly omitted all reference in his remarks to the locomotive I will make a few remarks about it.

You may think that the greatest point of difficulty in connection with the electrical locomotive today is with the electrical features of it, that is, the design of motors and control, but it may be questioned whether that is absolutely true. There is no question about it that the electrical features have required most careful designing. But I believe the one point that is attracting as much attention from our locomotive designers at the present time as any other, is the method of connecting the motors to the drive wheels. Now, what is the best connection for transmitting the power? We have in the New York Central locomotive probably the simplest. There the field of the motor is made a part of the frame of the locomotive. The armature is pressed on the axle. That has some difficulties in the way of additional dead weight on the axle, which some people claim has been very detrimental to the road bed. At any rate when we discussed with our good friend Mr. McHenry the design of new locomotives, there was one specification which he absolutely insisted on, there must be no dead weight on the axles excepting the axles themselves and the wheels; the motors must be spring supported. That specification has been maintained, and I must say I am in absolute accord with his views on the matter, that there should not be unnecessary dead weight on the axles.

The design of the original locomotive was also limited by the insistence on having no gears. That I believe was a very good thing. I think we have made a greater success of the proposition than we should have done at that time with gears. The motors have been mounted on quills. As probably most of you are familiar with the design I will not attempt to explain it in detail, but the motor is concentric with the axle and drives the wheels through springs. Now, the later forms of locomotives have a gear reduction. This 071 as it is familiarly known has the motors arranged directly above the axle and they are geared down to the quills; the springs connecting the quills with the wheels are long and quite flexible, so that there is sufficient play there to permit the motor to be mounted rigidly on the frame of the locomotive and to move with it, allowing an inch and a half of play either above or below the normal position. That is the easiest riding locomotive I was ever on and I believe I have ridden on practically all of the different types of electric locomotives in the world at this time. Without any question it is the easiest; that is, as far as the comfort of a man in the cab is concerned, and I believe ease on the road-bed as well.

Another type of drive which is now being used to some extent in this country and a great deal abroad is the side rod type. That is a reversion to the old steam locomotive practice. We found that some railroad people were never going to be satisfied until they had side rods on their locomotives. Without them the thing didn't look like a locomotive. Mr. Murray even criticized our first design of locomotive because he said it didn't have any distinctive appearance about it, it didn't look like a locomotive.

Now, this side rod type has been applied on the Pennsylvania electrification at the New York terminal and it is doing very good work indeed. Those locomotives are probably more powerful than any other in the world. They will pull an 800-ton train up a two per cent grade at 30 to 40 miles an hour; they will start the train equally well. That means a good deal when you consider there are only about 100 tons on the drivers and it requires 60 to 70 thousand pounds draw bar pull to do that.

We have been extremely fortunate and I want to say the whole railway world owes Mr. E. H. McHenry, the Vice-President of the New York, New Haven and Hartford, a debt of gratitude. He has been perfectly free to accept the responsibility and to afford all of the contractors the greatest latitude in working out designs, to afford them the opportunity to try new devices and new designs which appeared to have merit. At this time there are orders placed and locomotives practically completed of several different designs, or rather modifications of one or two designs, they are more samples. They have that 071 type which was built as a sample but was found so good that they built the Hoosac Tunnel locomotives identical with it, mechanically and electrically, except that they are straight alternating current instead of alternating current-direct current. They have now a side rod locomotive. 070 has two very large motors driving through side rods similar to the Pennsylvania locomotives. There is in the shop a switcher locomotive which is illustrated in the paper which has the four motors above the axles geared down to quills.

There is the 072 similar to the 071, but with some modifications as found desirable and possible after the experience of building one.

Then there is another locomotive which I feel is going to be one of the best that we have yet been able to produce and that will be known as 069. It is going to be an " earlier " type but it is not quite finished yet. It looks at first thought as if it might be a mistake, as if somebody's slide rule had slipped a little bit, but I don't think that is the case. We have eight motors on that locomotive instead of two which the side rod locomotive takes. We have two motors for each driving axle. The motors are mounted in pairs and geared directly to the quills. We use two motors to replace the one large one. The reason for that is plain, when you consider the matter. The space between the wheels on a locomotive is very limited and when you come to build large motors you find that a very large portion of that space must be used in gears. For instance the large motors on that 071 have two gears of 4¾-in. face each, so that there are 9½ in. gear space; add to that the space required for gear cases and you find you haven't very much space left for the motor. That means that the motor must be made very large in diameter in order to get the torque, which runs up the peripheral speed of the armature and cuts down the output in that way. The smaller motors have been well and thoroughly developed for car uses and they do not require as large a gear. By mounting two of these motors together we can connect them both to one large gear of very much narrower face than the sum of the two gears on the large motor, so that we are able to utilize this space much more efficiently between the wheels than would be possible with a large motor, and we find there is a very material reduction in the weight made possible by that arrangement.

That is, however, not the only new feature about this locomotive. The running gear is quite different. It has four pairs of drivers. There are two middle drivers which are mounted in the rigid frame that the cab is mounted on; instead of having two six wheel trucks as this 071 has there are four drive wheels in the middle of the locomotive, and at each end there is one driving axle and a pony which are mounted in a truck by themselves and swing more like a Mallet locomotive. It has something like a Mallet hinge in there; it is a modification of that idea, but it results in a very light flexible locomotive which I think is going to be a winner. The control instead of being complicated by the number of motors is very much simplified and reduced in weight as well, so everything tends to make that an extremely light locomotive, one that you are going to hear from shortly.

You would be surprised at the interest that is being taken all over Europe and this continent as well on the subject of electrification. In South America they are working on it; they have a number of large propositions and are quite wide awake in Chili, Peru, Brazil and in the Argentine. They are doing wonderful things down there. In Europe they are very much alive to the subject, and with the exception of the Italian State railways all countries have adopted single phase as the medium for the electrification of railways. So that we are not alone in this country in advocating that system. It is the standard which has been selected after great thought and study by the Germans, the Swiss, the French and the Swedes and it has been introduced in England. I received a paper a couple of weeks ago which follows exactly the same line with Mr. Murray's. It is written by Philip Dawson. He is a prominent engineer in London who has superintended the electrification of the branch of the London, Brighton & South Coast Railway there. That is a line at present only about nine miles in length, almost within the limits of the City of London. They adopted for that the single phase system, in spite of the most tremendous opposition among engineers there which has been practically of the same nature as in this country. They adopted it and after several years, for things move very slowly in the old country, they put it in service about a year and a half ago, and I had the great pleasure of going over the line with Mr. Dawson last spring, and he explained to me how well they were operating, and I could see from the results they were getting that everything was running in splendid shape. The work was not pushed as fast as it was on the New Haven road and they had the advantage of the experience of other roads which had been operated before they started out, so that I don't think they have had as many interruptions and as much grief as we had on the New Haven road. But they are getting splendid results and Mr. Dawson's paper is a strong endorsement of the system. The result is just the same as it is in New Haven. They are going to extend it; they are going to extend it right away, and they have voted the money for that purpose. It is a very noteworthy point, that single phase railways are as a rule extending their lines, but it is not very often the case with the direct current lines; when it comes to the electrification of steam railways they hold on a long time before they extend them beyond the limitations which are required by law. The B. & O. Railway electrified its tunnel at Baltimore ten or fifteen years ago and it has the same length of electrification today as it did then. It is a success as far as it goes. The New York Central electrified at the same time that the New Haven did, or somewhat before, but we don't hear any talk of their extending their electrification, but the New Haven electrified with the single phase system is pushing right ahead. They have a system which is flexible and it will admit of the greatest degree of extension. The London, Brighton & South Coast in England is the same way; they can expand and extend their lines.

I have been making a few calculations lately about the loss in power. On a direct current system or any system, with 1,500 volts on the line, with a line say 20 miles long, with two Number 0000 wires for overhead conductors, with a station at each end of that 20 mile line, you run a single car over that line at schedule speed of about 40 miles an hour and you will lose five per cent of your energy in the line. That is with a line only 20 miles long with a sub-station at each end and about 1,500 volts on the line, and only one car. If you run two cars in one train it will double your percentage of loss. Take a single phase system with 11,000 volts on the line, a 40 mile line feeding from one end only, and your average loss in that line with a car going over it will probably not be more than one half what it would be with the single car on the 20 mile stretch.

Single phase equipment is unquestionably heavy; it is heavier than the direct current or three-phase equipment. For that reason it requires more power to carry the car over the line, but when you consider the loss in the line between the car and the substation you will find it is on the other side of the ledger before you get past the substation. There is more power required for the low voltage system. You have got to have high voltage in order to make electrification a financial success.

B. G. Lamme: Mr. Storer has already discussed the locomotive very fully and therefore I will confine my remarks to certain general features of the system, which Mr. Murray has mentioned, but has not emphasized as fully as might be.

Take, for instance, the original system proposed for the New Haven Railway. It was planned to use high voltage directly from the generator, 11,000 volts at 25 cycles feeding directly into the overhead line. One terminal of the generator was to be permanently grounded. This meant that the supply system contemplated an 11,000 volt generating plant with one terminal permanently grounded, connected without transformers to a trolley system comprising over 100 miles of 11,000 volt overhead line. This was a new and untested condition. A further feature contemplated in this system was that it had to be capable of almost unlimited expansion without undue loss or excessive complication.

The locomotive was also a new type of apparatus, but designed along the lines laid out originally for the single-phase system, in which single-phase commutator motors with voltage control were to be used. By this control the speed of the locomotive was to be varied over any range from zero to maximum speed, simply by varying the voltage supplied to the motors by means of a step-down transformer on the locomotive itself. At the same time the locomotive was designed to operate on 600 volts direct current as well as on 11,000 volts, 25 cycles alternating current.

This New Haven system was installed along the above lines and has been carried through to an entirely successful operating condition and, while certain minor changes have been made, it will be almost impossible for an electrical layman, as you might call him, to find these changes. I mean by this, that if he had looked over the system rather completely in the first place and would look over the present system and equipment, it would be difficult for him to see any differences or changes which would appeal to him as being of any controlling importance. However, a number of changes from the original installation have been made, and I wish to call attention to the fact that these changes have consisted almost entirely of *additions* to the system and equipment to meet unknown or new conditions which have developed since the system was first installed, that is, these changes have not been made to correct what might be called mistakes or errors in the original layout. Also, a number of the modifications may have been in the nature of developments which will find application in other fields besides single-phase railway work. Take, for example, the generating plant. In order to adapt very large capacity generators for single-phase railway operation, new problems were encountered which had not proven serious in small size machines. For instance, complete cage dampers were put on the rotors of the generators to repress the pulsations due to the single-phase armature reaction. Since these machines were installed it has become a recognized practice in all very large high-speed single-phase generators to equip the rotors with some sort of cage dampers. Such generators are coming into use for other purposes besides railway work, electrochemical work and electrofusion being examples.

Take another feature of the generating plant, namely, the addition of choke coils in the leads between the generator and the overhead system, as was described in connection with Mr. Murray's former paper before the American Institute in December 1909. These choke coils were added for the purpose of reducing the enormous current rushes which occurred in the case of short circuit on the line. This practice of using choke coils for the protection of large turbo-generators is now being applied in a number of cases in connection with three-phase high voltage machines. The application of this principle which is used in the New Haven single-phase plant is now being carried into other fields than single-phase railway work.

Take another feature, namely, the selective system which is developed in connection with the New Haven overhead system. In this system, in case of a short circuit, a resistance was introduced to take up the load before opening the circuit. The object was to avoid suddenly opening an enormous inductive load, with consequent possible disturbances on the generators and system. In order to open the circuit the inductive load was first transformed to an energy load by means of the introduction of resistance, and then this energy load, of considerably reduced amount, was opened by the breakers. This arrangement contains the germ of a practice which may eventually be carried into the whole field of transmission work.

Considering the transmission line, the use of the steel trolley wire below the main wire may be regarded as an addition pure and simple, and a very helpful addition from a mechanical standpoint. The original copper trolley wire served two purposes, namely, as a feeder or conductor, and as a contact wire for supplying current to the locomotive. The addition of the steel wire takes away from the copper wire its function of a contact wire, but it still serves its function as a conductor. The copper wire could not be taken out and the steel put in place of it, as the low resistance of the copper conductor is needed. Therefore, the copper still serves its more important function and the steel wire placed beneath it takes care of the mechanical requirements.

In the locomotives a few changes have been made since the original installation but they have been of a comparatively minor nature. The principal changes have been in the nature of additions rather than modifications. For example, part of the control system was increased in carrying capacity on account of the fact that the motor capacity actually proved greater, by about 15 per cent, than originally expected. The change in the control to take advantage of this increased capacity cannot be charged to a mistake or error, but should be credited as an improvement to obtain increased capacity. The original guaranteed continuous capacity of the locomotive motors was about 830 amperes. Some of these motors, on actual test, showed a continuous rating of approximately 1,000 amperes. This increase in capacity over what was proposed can now be taken advantage of in the operation of the system.

In connection with the original overhead system there was considerable talk about the possible large line drop. In practice, that question has not troubled anyone. A more serious trouble has been that the line drop has been very small, so that in case of short circuit anywhere on the line, enormous current rushes would occur which were destruction to the system. These were later taken care of by the choke coils and the selective system, as mentioned before. This low line drop, however, is just what is required if extensions are to be made in this system. Mr. Murray now announces that the present overhead system is to be continued down into the Harlem Yards, and his figures indicate that even with the enormous extension which is contemplated the maximum line drop will still be comparatively small.

Taking this system as a whole, it may be noted that the original voltage of 11,000 has been maintained; also, the original frequency of 25 cycles. No transformers had been added and the system can be extended as originally intended. The fact that the 100 miles of overhead work is now being increased to 500 miles without transformers shows the flexibility of the system. In all the history of electrical engineering I do not know of any undertaking which had as many new and untried features as this system has, which has been carried through to success with as close adherence to the original lines.

There is one feature in connection with the generating plant which has not had its full significance brought out before. I refer to the use of 11,000 volt machines with one terminal grounded. These generators have three-phase armature windings of the star type with one of the three terminals permanently grounded. Two of the legs of the star are used for the single-phase circuit, while the third leg is used in connection with certain three-phase work. Across the railway phase the potential is regulated for 11,000 volts normal, by means of an automatic regulator in connection with the fields of the generator. The third leg gives a little higher voltage normally, due to the small load which it carries at present. In consequence, its voltage is usually somewhere between 11,000 and 12,000 volts. Assuming this at 11,000 volts, then in these machines we have an equivalent, as far as insulation stresses go, of a three-phase generator with grounded neutral *with* 11,000 *volts between the neutral and the terminals*. This therefore is practically the equivalent of *a* 19,000 *volt three-phase generator with the neutral grounded*. It is more than this, as it is the equivalent of a 19,000 volt machine with the neutral grounded and *with the terminals tied directly to* 100 *miles of* 11,000 *volt overhead system without the interposition of transformers*. This is a very abnormal condition compared with anything that is being done in this country at present. 16,500 volts is the highest generator now used on a large scale, as far as I know. But here we are actually running under conditions corresponding to

19,000 volts with the hardest kind of service and with an overhead line without transformers which is going to be extended to about 500 miles. Under these conditions the generating plant has made an extremely good record, as indicated by Mr. Murray in his table of delays due to power house. I may say that for about two years, or possibly more, there has been practically no trouble as far as the generators are concerned; that is, any trouble which would shut down the system. There has been one breakdown in one machine, but a careful examination of this one case developed no cause for the breakdown other than a damage to the insulation in originally putting the coil on the machine. There were no signs of deterioration of the insulation, and the insulating materials on the damaged coil appeared to be as sound and flexible as when first put on. So here we are running machines at the equivalent of 19,000 volts on a three-phase system, and during two years there has been continuous service. This is a most excellent record. If we compare this with a late practice, now being advocated here and there, of winding large turbo generators for low voltage, such as 2,200 volts, and then stepping up to voltages, even as low as 6,600 volts, we can see what a wonderful thing this New Haven operation is. In some cases at the present time, 11,000 volts, or even 6,600 volts on the generator, is being condemned as bad practice because of dangers from line voltage, surges, lightning and such things, but in this New Haven plant there are 100 miles of overhead system under conditions where it is exposed to surges of the worst sort.

Referring again to the locomotives, the motors were popularly considered as the questionable feature of the whole system. Of the first type of locomotive, 41 were built, all of the gearless type with four motors each. The motors furnished, which were 250 to 300 h.p. were by far the largest up to that time. These motors were supplied with the so-called resistance leads which were considered by many to be a very harmful feature and a source of great loss. These locomotives have been in operation between three and four years and as far as we have had an opportunity to examine the resistance leads on the armatures of these locomotives they have shown no signs of over-heating or undue loss. In fact, in one case which I examined personally the copper winding showed more evidence of heating than the resistance leads. It should be borne in mind also that at times these motors have been very heavily overloaded. The record as a whole may be considered as good as that of corresponding direct current motors.

One very good feature has developed in these single-phase locomotive motors, namely, they are able to commutate well over an extremely wide range of speed. In the ordinary direct current motor of the non-interpole type, the commutating conditions become perceptibly worse as the motor speed is increased when carrying a large current. On the single-phase motor this condition is not encountered to the same extent. The short circuit current in the resistance leads decreases as the speed is increased so that the reduction in such current with higher speed compensates, to a considerable extent, for the effect of the increase in speed, so that the commutation as a whole seems to be equally good from very low speed up to very high speeds. This is of particular advantage in a system where voltage control is used, for it allows us to push up the voltage applied to the motors whenever there is occasion to do so.

Mr. Murray mentioned a new locomotive of the side-rod type, with two large motors. These motors are of nominally 600 h.p. continuous rating at about 200 revolutions at normal voltage. Claims have been made from time to time that with 25 cycles it was not possible nor practicable to build single-phase motors of more than 200 or 300 h.p. continuous rating, but tests on these 600 h.p-motors indicate that they work just as well as motors of 100 h.p., for instance. These motors have been loaded up to 100 per cent overload current and they commutate just as well as smaller ones.

In conclusion, I will say that the single-phase system in this country has its greatest example in the New Haven electrification. There are also a number of smaller systems which use single-phase railway motors, such as the Spokane & Inland Railway in the far West, and the Sarnia Tunnel near Detroit, which uses single-phase electric locomotives entirely. In Europe they have not put the single-phase system into commercial use on as large scale as in America, but in a number of European countries the single-phase system already has been adopted as standard for heavy railway work, and they are expecting to install the system on a comparatively heavy scale in the near future. Although the experience in Europe with this system is as yet more limited than in this country, yet it has satisfied them that the system can be adopted for main railway electrification.

W. S. Murray: With the exception of Messrs. Sprague and Katte, those who have contributed to the discussion—both on the American and European side—seem to be in general agreement with the author, but for a few exceptions with reference to details of the system. The author is left, after reading the discussion, with the impression that single-phase power is correctly used when applied to trunk line roads inclusive of terminal, suburban and yard rails. The opening paragraph of the paper advocates this application, and it is most gratifying to find the general support of this recommendation.

Mr. Sprague implies that I said that the time has come when the electrical engineer can say that there is but one system of electrification to meet all the varied problems of railroading. Nowhere in the paper is such a statement made, nor one that could be interpreted to involve such a conclusion. It should be remembered that street railways and trunk lines are two entirely different propositions. In answer to the criticism that no mention of costs is made in the paper I call attention to that part of my paper devoted to electrification costs and under this is discussed power house, line and locomotive costs, and with the closing remarks that "not until the electrical system of the New Haven Road is a unit in itself, rather than a mixed service of steam and electricity, can its true economies of electrical traction be discussed". An extension to New Haven will give this, though even then the highest economies of the single-phase system cannot be realized, due to the necessity of a large portion of locomotives and multiple unit equipment being required to do dual service on alternating-current and direct-current lines. As the electrification only covers 1/5 of the zone ultimately to be included it is not expected that information as to operating costs would be of great value. It does not advance the application of electricity to railroads to proclaim the disappointment at not receiving data which is practically unavailable to the railroad company itself.

Mr. Sprague summarizes the railway system advocated in the paper by the following characteristics:

1. "Single phase transmission at a potential limited by the requirements of the trolley wire from central stations equipped with generators built with variable voltages and operated with grounded circuits".

2. "The abolition of the step-up and step-down transformers."

3. "A potential of 11,000 volts or higher on a trolley line in contiguous territories, but with entire freedom to change that voltage to something different on remote lines."

4. "The abolition of the single-phase 25 cycle motor and the substitution therefore, as a possibility in the near or the dim future, of a single phase induction motor, or in lieu of that the much criticized direct-current motor supplied by a mercury rectifier or its equivalent."

Commenting on these characteristics it should be noted in connection with (1) that variable voltage generators were not included. The New Haven road has used and intends to use only constant potential generators unless later conditions require otherwise. With reference to (2), the system described does not rule out the step-up or step-down transformer. We are contemplating using some shortly but the distances of our transmissions to date are short enough to be economical without them.

With reference to (3) Mr. Sprague states the situation correctly.

With reference to (4). It is common knowledge that the cost of power stations of the single-phase or three-phase type may be equated. It is common knowledge that single phase propulsion equipment is more costly than direct-current equipment; ***but it is also common knowledge among those who have had practical experience with the accounts incident to alternating-current and direct-current operation that it is in the distribution system that the economy of single-phase traction lies.***

Having admitted that direct-current propulsion equipment is less costly than alternating-current, and notwithstanding this fact that the *single-phase system* is more economical than the *direct-current system*, why, if 25 cycles is the frequency more conducive toward a reduction in propulsion apparatus cost for the reasons mentioned in the paper, should it not be advocated?

Thus I believe that the discussion has wandered from the particular points and system described in my original paper.

Mr. Katte criticises the absence from my paper of figures for relative costs per ton mile of steam and electric trains in similar services. Yet in the same paragraph of his discussion says " Here I may add that cost figures for comparative performances on the N. Y. C. system are not available for the reason that the service is still mixed steam and electric ", thus ignoring the fact that the same difficulty exists on the New Haven. There is in addition the complication due to the operation with both single-phase and direct current.

In connection with the subject of train delays which is brought out in Mr. Katte's tables due consideration should be given to the relative ages of the two systems employed. It is not remiss to mention here that of all the roads entering New York City, the New Haven had last year the record of handling the highest percentage of trains on time.

Mr. Katte claims a higher efficiency for the New York Central locomotives than for the New Haven. He states that trains of similar weight are handled by the New York Central at an average energy consumption of 23 watt-hr. per ton mile whereas he gives figures for the alternating-current run between Woodlawn and Stamford on the New Haven of 32.5 watt-hr. per ton mile. I do not know where the figure for the New Haven services was obtained but I deny that for equal conditions of load and service the New Haven *takes 42 per cent more power than the New York Central.*

My own calculations are based on the fact that it is conceded that the alternating-current motor has a range of efficiency 2 per cent below that of the direct-current motor. The published curves of the New Haven and New York Central locomotives show this. Under the condition named the watt-hours per ton mile are a straight function of the locomotive efficiency, which means a difference of 2 per cent as against 42 per cent. Moreover, carrying these calculations back to the power house the fact should be borne in mind that a 15 per cent saving in transmission losses offsets the loss in the motor over six times. The cost of the actual coal burning is proportional to the energy generated at the power station and not to that consumed by the locomotives.

I wish to take this opportunity of thanking Messrs. Fritch, Woodbury, Jackson, Storer, Lieb, Scott, Dawson, Smith, Taylor, Lamme, Graftio, Kapp and Steinmetz for their liberal discussion of the paper. I find myself with the feeling, after reading their contribution to the discussion, that in the specific matter of what type of electrification should be applied to trunk line rails inclusive of terminal, suburban and yard service, that if not entirely individually sustaining, their general conclusion sustains the author's point of view. Some of these gentlemen have differed with the author, and quite decidedly in points of detail, and for this difference of opinion I of course hold only the highest respect and acknowledge the valuable information presented.

Briefly commenting on the discussion of the gentlemen above referred to, it is extremely gratifying to find Mr. Fritch in agreement with my recommendations as to standardization. He epitomizes the situation in saying: "As long as the system is not established you are simply furnishing ammunition for those who do not desire to electrify." Particularly pertinent do I consider Mr. Fritch's remarks with reference to the electrification of yards. By the use of the overhead system the problems of readjustment of obstacle and equipment clearances, the disbarment of certain classes of rolling stock and the general complication and awkwardness incident to a ground conductor are eliminated and the yards and terminals can be treated, in so far as ground conditions are concerned, in a manner exactly as in the past. It is common knowledge that in yards the least amount of money possible is spent on track and ballast—two items in intimate difficult relationship with reference to the adjustment of the ground conductor (third rail) whose location is a matter of the fraction of an inch, while in the case of the overhead wire its unit of adjustment is the foot. The simplicity of the overhead construction and its susceptibility to a standardization for all railroads is easily apparent.

I have read with a great deal of interest and instruction Mr. Woodbridge's discussion with reference to the matter of storage batteries for trunk lines, and I am interested to note that he believes there are places where the battery would be of economic value. It is due Mr. Woodbridge for me to say that I had the specific cases of the New Haven and the New York Central electrifications in mind. In the case of the former it would have been quite uneconomical, and having conferred with the New York Central engineers about the installations of the batteries upon their lines, I was advised that had they to do it over they would not be installed, and in their contemplated extensions no batteries would be installed. It might be well to say here also that both the New Haven and the New York Central roads are of a class typical (in the heavier form) of trunk lines I have had in mind in connection with recommendations made in the paper.

With reference to the closing paragraph of Mr. Smith's discussion, which seems to epitomize what has preceded it, I would say I am heartily in agreement with Mr. Smith that the future may develop some method less costly both as to investment and daily operation than the system now employed by the New Haven road for the electrical operation of its trains. I should indeed be greatly disappointed if what we have today is not greatly improved upon in the future. Let us, however, while hoping for better things, not hesitate to go ahead with the foundations already laid. Because we may believe what we have is the correct underlying principle and advance it in every way in the field of practical application, cannot possibly dim the chances of some better system of the future to take its place.

I feel that the underlying principles of the single-phase system have been sufficiently exposed to ratify its post, and to build on them in the future. In my opinion it will be more costly to wait than to go ahead. It cannot be denied that a universal standard of trunk line electrification would be most acceptable to all railroads. With the exception of a very few engineers, we hear it said that all three systems will work—the direct current, three-phase and single-phase. If this is so, then let us elect one and apply it to trunk lines to be electrified, and I believe we have enough data to date to show that the single-phase for this class of electrification has inherent in it the economic factors necessary to its selection as the standard. It seems to me the time is at hand, or very nearly, when we must select and not enumerate. There is a limit to the capacity of any ship. If she has to carry much more discussion she may sink.

I am very glad to have Dr. Steinmetz' agreement with reference to frequency. The reasons he has presented, together with those mentioned in the paper in connection with the possible future introduction of the induction or direct-current motor, still using the single phase system of distribution, would seem to be entirely consistent.

I think Mr. Taylor has brought out a good point of information, with reference to the difference between phase and voltage balance, and while what he says is quite true, I do not see that it makes necessary any change in the quotation he has cited from the paper.

With reference to Mr. Lamme's and Mr. Storer's discussion, I can only express my thanks for the interesting points brought out with reference to the generator and locomotive features of the system; the developments in these departments being due almost entirely to the patience, pluck and ingenuity of these gentlemen.

With reference to Mr. Graftio's discussion, I cannot see how his "Queen" (the steam locomotive) can be used as a reason against a choice of system for standardization. His "Queen" includes in it all the variable (speed and torque) characteristics that have unified steam standardization, and they can be all duplicated in single-phase locomotives.

Mr. Kapp's conclusion with reference to standardization is most encouraging. It is interesting to note that in Europe there is a strong trend to standardize and it is most gratifying to know that for trunk lines the type of electrification has practically been settled upon in favor of single-phase.

The paper was presented to give up to those who have responsibilities, or to whom later responsibility for electrification of steam road bed may come, information that to the date of the paper had been collecting in my files. Minute costs relating to investment and operation, due to the incomplete state of electric engine stage (division run) was avoided and this feature of electrification was touched upon only in the most general way. The now acknowledged and indisputable principles of economy inherent to the single-phase system as applied to the trunk line system is the guarantor of the results that may be reasonably expected when a sufficient time has passed to stretch its length into an engine stage.

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AUTOMATIC MOTOR CONTROL FOR DIRECT CURRENT MOTORS

BY ARTHUR C. EASTWOOD

"The flexibility of the electric motor" is a well worn phrase and one which is quite commonly accepted at its face value. As a matter of fact an electric motor has quite definite characteristics, and these characteristics usually must be modified by some form of controller to adapt a given motor to varying conditions.

At the present time there is probably no branch of industry in which a machine is used which has not been invaded by the electric motor. This general use of electric motors carries with it the fact that these motors are daily started and controlled by al classes of operators, from the most highly skilled to the most ignorant and careless.

Where a manually operated starter is used, the rapidity with which the starting resistance is cut out, and hence the accelerating current, is left to the judgment of the operator. If the operator be ignorant or careless, damage to the motor and to the driven machine may result from cutting out the starting resistance too rapidly. On the other hand, if he is over-cautious he may consume more than the necessary period in cutting out the starting resistance, causing a waste of time, and possibly also a burned out rheostat. Or, if an operator be transferred from a machine which has small inertia and starts easily to a machine or tool which has great inertia (such as a punch press having a heavy flywheel), if he has not been previously instructed in the starting of the heavy machine, this part of his education may prove expensive to his employer.

Where motors are to be reversed as well as simply started, the possibility of damage to the motor and driven machinery, due to careless manipulation of the controller, is much greater than is the case in simple starting because, if the motor connections be suddenly reversed while the motor is running, the counter e.m.f. of the armature becomes additive to the line voltage until such time as the armature has been brought to rest. In the case of series wound motors running under light load or of shunt wound motors running with weakened field, the voltage impressed on the armature and the starting resistance may readily be several times the normal line voltage. Destructive currents may therefore occur if the resistance is cut out too rapidly in the reverse direction.

Obviously the ideal arrangement for starting or reversing a motor is a starter or controller which will " do the thinking for the operator ", leaving it to him to simply push a lever to start the motor and pull the lever to stop the motor.

In the case of any motor-driven machine or tool there is a maximum safe accelerating current which should not be exceeded. This maximum safe current may be determined by the ability of the motor to commutate properly, or it may be determined by other conditions such as the slipping point of belts in a belt drive.

The ideal starter or controller should be so arranged that this maximum safe current cannot be exceeded. It should also be so arranged, in the interests of efficiency both as to current and to time, that the current during acceleration will be kept as closely as practicable up to the safe maximum value. In other words, the starter must automatically interpret load conditions. If the load be light the starter must see to it that the motor is brought up to speed quickly, while if the load be heavy, the period of acceleration must be correspondingly longer.

In the past there have been several types of starters and controllers which have approximated the characteristics above detailed. First may be mentioned the " time element " type in which the starting resistance is always cut out in a fixed period of time. This type of starter falls short of the ideal in that it cannot adapt itself automatically to variation in load.

Second, the " counter e.m.f. " type in which the starting resistance is cut out by a magnet or magnets which respond to the counter e.m.f. of the motor. This type of starter or controller has done good work in elevator service but is open to the objection that its action is disturbed by fluctuation in line voltage.

Third, the "current limit" type in which the cutting out of the starting resistance is governed by the motor current. This type is generally characterized by a number of shunt-wound magnetically-operated switches which control the starting resistance and one or more series relays which respond to the motor current and serve to check the successive closure of the resistance switches when the accelerating current exceeds a predetermined maximum. This type, which I will call the "shunt current limit type" in order to distinguish it from another type to be later considered, approaches the ideal very closely and has been the direct means of introducing the electric motor in many applications where steam and hydraulic power had been the previous standard.

A specific instance in point is found in the introduction of the motor drive for "reversing mill tables" in steel mills. These tables are reversed several thousand times a day, and up to less than ten years ago small steam engines were universally used to drive them. It had been attempted to use motors for the purpose, but with manually operated controllers and operators accustomed to operate hydraulic or steam valves both the motors and the machinery were so severely punished by excessive currents, due to cutting out the starting resistance too rapidly at the time of reversal, that the arrangement was operative, in a practical sense, only in the hands of a skilled and careful operator, and was too delicate to be used as standard equipment in a steel mill. The advent of the automatic magnetic controller, which automatically keeps the acceleration current within fixed limits, overcame the difficulty. With this type of control the master controller can be operated as rapidly and roughly as a hydraulic valve with no danger to the motor or the driven machine. No particular skill is required of the operator in starting or reversing the motor. It is left to him to simply push a lever to start the motor and pull a lever to reverse the motor. He is therefore free to devote all of his attention and skill to the business of working steel. He is no longer a combined motorman and steel-worker but a steel-worker pure and simple.

In addition to this advantage of the automatic controller, in that it eliminates the necessity for skill on the part of its operator, it carried with it other advantages having a direct bearing on increase in output. Among these advantages may be mentioned the following:

1. The master-controller is small and easily operated. The

physical endurance of the operator is eliminated as a factor in the output of the mill.

2. By keeping the accelerating current as nearly as practicable up to a safe maximum the motor is always brought up to speed in minimum time.

3. By keeping the current at the instant of reversal within safe limits delays due to both electrical and mechanical breakdowns are greatly reduced.

With these very practical advantages demonstrated, the electric motor with automatic control was very promptly adopted for the drive of mill tables, and is now the accepted standard in steel mills for this and many other drives.

The *shunt type of current limit controller* accomplishes the results for which it is intended in a thoroughly practical and satisfactory manner, but its general use is precluded at the present time by the fact that it is a highly organized piece of apparatus which is too complicated to be readily understood by an ordinary electrician. In other words, while the shunt type of current limit controller eliminates skill on the part of its operator, it requires a somewhat skilled electrician for its proper maintenance.

Some recent developments in automatic motor control of the current limit type which result in a very material simplification of the controller are described below. This new type of automatic controller or starter is known as the *series current limit type* in view of the fact that the magnetic switches which control the acceleration are series wound and their windings are connected in series with the motor to be started or controlled.

This type of controller is made possible by a type of magnetically-operated switch which possesses remarkable characteristics.

This switch acts not only as a switch for closing a circuit and holding it closed, but acts also as a current limit relay or so-called "throttle". If the current which flows through the winding of the switch is below a certain critical value the switch will close instantly, while if the current is above this critical value the switch will "lock out" or refuse to close till the current has been reduced to the critical value. Means are provided whereby the critical value of current below which the switch will close and above which the switch will lock out may be readily adjusted, thereby adjusting the accelerating current taken by the motor.

Fig. 1 is a cross-sectional view of a typical switch of this type. In this illustration *I* is the operating coil, which as previously mentioned is so wound as to adapt it for connection in series with the motor to be controlled. This winding is carried by a brass tube within which the core *E* is free to reciprocate vertically. The upper end of the core *E* carries a non-magnetic stud to which is attached a copper contact plate *G*, adapted to make contact with a pair of contact brushes *H* when the switch is closed. The lower end of the core *E* is reduced in cross-section and forms a stem *F* which meets the body of the core to form a shoulder. The stem *F* passes into a hollow adjustable plug *C* which is of magnetic material. The winding of the switch is enclosed and protected by a semi-cylindrical iron casing *A* which also constitutes the return member of the magnetic circuit. The upper member of the frame or case *A* is provided

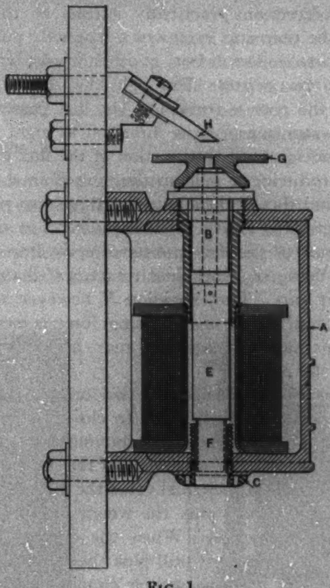


FIG. 1

with a plug or pole piece *B* of magnetic material. When current flows through the winding *I* magnetic flux passes between the plug *B* and the upper face of the core *E*. Substantially all of this flux is normal to the face of the core *E* and is effective in producing a magnetic pull tending to close the switch. At the lower end of the core, however, the flux has two paths. One of these paths is from the horizontal portion of the frame *A* into the sleeve or hollow plug *C*, and from the upper face of this sleeve through an air gap into the shoulder on the core. This portion of the flux takes a direction practically normal to the face of the shoulder on the core and produces a magnetic pull which tends to move the core downward or, in other words, tends to prevent actuation of the switch. Through the second path at the lower end of the core a portion of the flux passes directly into the stem or extension *F* in a direction at right angles to the direction of motion, and this portion of the flux is therefore not effective in producing a pull on the core *E* in a vertical direction. The total flux divides between those two paths inversely as their reluctance. With a small current in the winding *I* substantially all of the flux passes directly into the extension *F*, this path being of much less reluctance than the path including the air gap. The extension *F*, however, is of restricted cross section and as the magnetizing force is increased the reluctance of this path increases and more and more of the flux is crowded into the air gap.

The core *E* is then acted upon by two forces—one the magnetic pull at its upper end which tends to close the switch, and the other made up of the weight of the moving parts plus the downward magnetic pull at the shoulder on the plunger. When the current is below a certain critical value the upward pull is greater than the downward pull plus the weight of the moving parts and the switch will close. When the current is above this critical value the downward pull plus the weight of the moving parts predominates and the switch cannot close.

The critical point below which the switch will close and above which it will "lock-out" is adjusted by screwing the adjustable plug *C* in or out which adjusts the lower air gap. This has the effect of altering the reluctance in the path including the air gap with respect to the reluctance of the path including the stem or extension *F*. Screwing in the plug and thereby shortening the air gap has the effect of decreasing the value of current at which the switch will "lock-out", while increasing the air gap has the effect of increasing the value of current at which the switch will "lock-out".

Fig. 2 is a reproduction of the operating curves of one of these switches. The ordinates of these curves read in amperes and the abscissas in fractions of an inch, showing the length of the lower air gap.

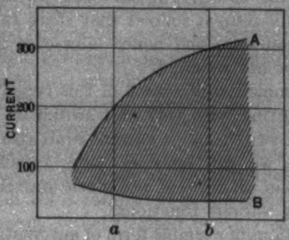


FIG. 2

The upper curve *A* is the "lock-out" curve, and the lower curve *B* shows minimum current at which the switch will close. The switch will close at any value of current between the two curves as measured on an ordinate corresponding to the length of air gap under consideration.

It will be observed that the curve *B* is a substantially horizontal line which shows that the minimum current at which the switch will close is very little affected by altering the lower air gap. The form and general pitch of the operating curve *B* are matters of design into which the diameter of the stem or extension at the lower end of the core relative to the diameter of the core at its upper end and also the location of the magnetizing winding relative to the two air gaps in the magnetic circuit enter as important factors.

FIG. 3

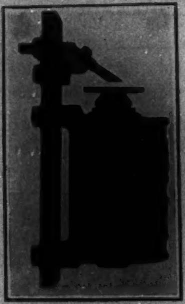


FIG. 4

After the switch has closed it is held closed through a substantially closed magnetic circuit and it will therefore be held closed till the current in its winding has fallen almost to zero. Since both the winding of the switch and also its contacts are in the controlled circuit and the switch will not open till the current has fallen to practically zero, it follows that there can be no arcing at the switch contacts, and hence blow-outs or other arc-rupturing devices are not required.

Figs. 3 and 4 illustrate a complete unit switch of this type in side and front elevation. Starting with this unit switch as a basis, the switch being both a switch and a current-limit relay combined in one mechanism, we will consider some typical combinations of these switches in the form of automatic starters and controllers for performing various functions.

Fig. 5 is a diagram of connections of a simple form of automatic motor starter in connection with a compound wound motor having the armature *A*, series field *F* and shunt field *f*. K is the starting switch which is closed by the operator to start the motor and is opened to stop the motor, this being the only part of the starter with which the operator has anything to do. *S*1, *S*2, and *S*3 are three automatic switches which control the starting resistance *R*. These switches are provided with series-wound actuating coils *C*1, *C*2 and *C*3 respectively. The switch *S*3 is also provided with a shunt-wound holding coil *H*3.

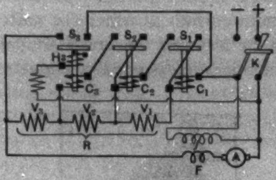


Fig. 5

When the starting switch *K* is closed current flows from the positive side of the switch through the armature and series field of the motor, the entire starting resistance *R* and the actuating winding *C*1 of switch *S*1 to the negative side of switch *K*. The motor should then start, and although the actuating winding of switch *S*1 is energized this switch will not close till the current has dropped to the value for which the switch is adjusted.

When switch *S*1 closes the first section of resistance *V*1 is short-circuited, the path of the current then being from the switch *K* through the armature and series field of the motor, the resistance sections *V*3 and *V*2, the winding *C*2 of switch *S*2, the contacts of switch *S*1 and the winding *C*1 of switch *S*1 to the switch *K*. The winding *C*2 of switch *S*2 is then energized and when the motor current has dropped to the value determined by the adjustment of the switch it will close, thus short-circuiting the section of resistance *V*2. The current then takes the following path: from the switch *K* through the armature and field of the motor, the resistance section *V*3, actuating winding *C*3 of switch *S*3, contacts and winding of switch *S*2, and contacts and winding of switch *S*1 to the switch *K*.

The actuating winding *C*3 of the last accelerating switch is thus energized and when the motor current has dropped to the predetermined accelerating value the switch *S*3 will close. As switch *S*3 closes the circuit through its shunt-wound holding coil *H*3 is completed at the contacts of the switch itself and the switch is held closed by this coil. The closure of switch *S*3 throws the motor across the line through the following path: from the positive side of switch *K*, through the armature and series field of the motor and the contacts of switch *S*3 to the negative line at switch *K*. The contacts of switch *S*3 are therefore the only contacts or connections in the motor circuit when the motor is running.

It will be observed also that closure of switch *S*3 short-circuits all three of the actuating coils *C*1, *C*2, and *C*3. Switches *S*1 and *S*2 therefore drop out, while switch *S*3 is held closed by its holding coil *H*3. It is also to be noted that switch *S*1 in closing closes the circuit through the actuating winding of switch *S*2, while switch *S*2 closes the circuit through the actuating winding of switch *S*3. The switches are thus compelled to close in orderly sequence without recourse to auxiliary or " interlock " contacts.

To stop the motor it is merely necessary to open the switch *K*. In case of failure of voltage the holding coil of switch *S*3 is de-energized and this switch opens, inserting all of the starting resistance *R* in series with the motor. When current is restored to the line (provided the operator has not previously opened the switch *K*) the motor will again be started automatically in the normal way. While Fig. 5 shows the connections for a compound-wound motor, it is evident that the same form of starter is equally applicable to shunt and series-wound motors. In the case of series-wound motors connected to loads which may be so reduced as to cause the motor to speed up dangerously, the starter can be very simply modified to protect against this. To accomplish this the holding coil of switch *S*3 is made a series coil and is connected in series with the contacts of the switch.

Since in a series motor the speed depends upon the current, the holding power of the holding coil will be weakened as the motor speeds up, and the coil may readily be proportioned so as to cause the switch $S3$ to open before a dangerous speed is reached.

A complete starter corresponding to the diagram of Fig. 5 is shown in Fig. 6.

As previously mentioned, there is no danger of arcing at the contacts of the accelerating switches, the motor circuit being initially closed and finally opened at the contacts of the operator's switch *K*. In the case of constantly running shunt or compound wound motors, a simple knife switch or its equivalent is suitable for the purpose where remote control is not a consideration. In applications where short moves of a heavy machine may be made, as, for instance, in setting up the work on a boring mill, provision must be made for the arcing at the operator's switch due to opening the motor circuit when the motor is generating but a small counter e.m.f. This can be taken care of by providing a specially constructed operator's switch having its contacts suitably protected against arcing, or preferably a type of starter illustrated in Figs. 7 and 12 is employed.

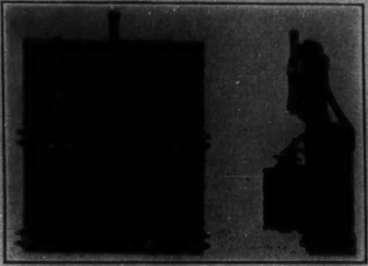


FIG. 6

In this form, in addition to the series-wound accelerating switches, a main switch or initial circuit-closer in the form of a shunt-wound magnetically operated switch or "contactor" is provided. This contactor provides for a quick opening of the circuit in the field of a powerful blow-out magnet such that heavy currents in an inductive circuit are opened promptly and with slight depreciation of contacts.

The use of this shunt-wound main switch makes it possible to use push-buttons or small pilot switches which are used by the operator in starting or stopping the motor. As many of these starting and stopping switches as desired may be placed at convenient points around a large machine or tool, adding much to both the facility and safety of operation. This type of starter is also adapted to remote control by means of a pressure gauge, float switch, or other devices which interpret conditions under which the motor is to be started and stopped. This form of starter is also very simply provided with overload protection, the circuit of the winding of the main switch being broken at the contacts of a small overload relay, as shown in the diagram Fig. 8.

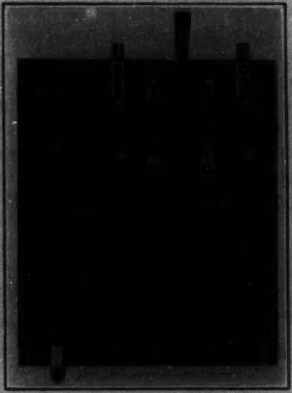


FIG. 7

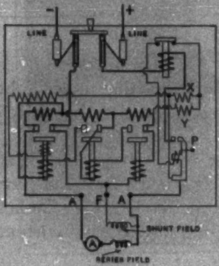


FIG. 8

The minimum number of accelerating switches which may be used in connection with a given motor depends rather upon the amount and character of the load than upon the size of the motor.

In general it may be said that when current limit acceleration is employed relatively very few subdivisions of resistance are required as compared with a manually operated starter. The number of subdivisions of the resistance in a manually operated starter is primarily determined as a matter of protecting the contacts of the starter itself. If too few subdivisions are used the drop between adjacent steps will be too high and serious burning or "bugging" of the contacts will follow.

The automatic starter or controller with current limit acceleration is of course free of this limitation, and in addition possesses the advantage, as far as the motor is concerned, of cutting out successive sections of resistance only when the current in the circuit is at the proper value.

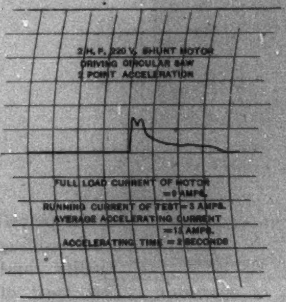


Fig. 9

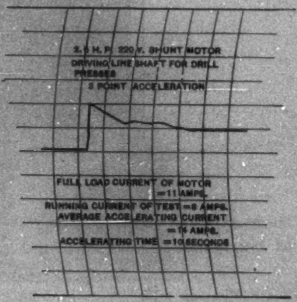


Fig. 10

For motors up to, say, five horse power, starting under light load or starting loads of small inertia, a single accelerating switch is sufficient.

For motors within the same range of horse power, starting at full load or starting loads of high inertia, (such as a machine equipped with a flywheel), two or even three accelerating switches may be required to keep the peaks of the accelerating current within prescribed limits.

Figs. 9, 10 and 11 are reproductions of accelerating current curves taken with a recording ammeter in the circuit of motors equipped with automatic starters of the "series current limit" type under consideration.

Fig. 9 shows the accelerating current curve of a two-h.p.

shunt motor driving a circular saw which starts under very light load. The starter in this case was equipped with but a single accelerating switch.

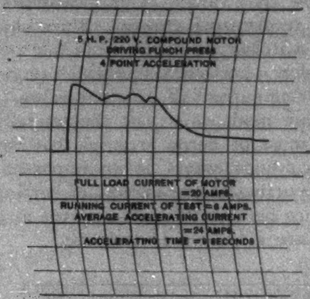


FIG. 11

Fig. 10 shows the accelerating current curve of a 2½ h.p. shunt wound motor driving a line shaft for light drill presses. The starter in this case was equipped with two accelerating switches, giving three points of acceleration including the operator's switch.

Fig. 11 shows the accelerating current curve of a five-h.p. compound wound motor driving a punch press, three accelerating switches being used. In general it may be said that for motors up to 25 h.p. three accelerating switches will be sufficient for all ordinary conditions, and for motors above this size from three to six or more switches may be required. In any case it does not pay to extend the number of switches beyond a point governed by the sensitiveness of the switch itself.

FIG. 12

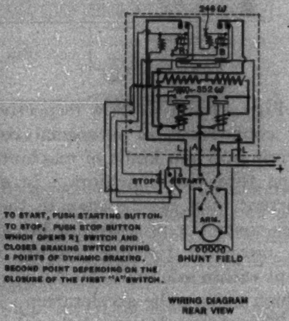

246 ω
352 ω
L
A
A
L
−
+
STOP
START
ARM.
SHUNT FIELD
TO START, PUSH STARTING BUTTON.
TO STOP, PUSH STOP BUTTON WHICH OPENS R1 SWITCH AND CLOSES BRAKING SWITCH GIVING 2 POINTS OF DYNAMIC BRAKING. SECOND POINT DEPENDING ON THE CLOSURE OF THE FIRST "A" SWITCH.
WIRING DIAGRAM
REAR VIEW

FIG. 13

The switch under consideration is sensitive well within ten per cent, that is to say, if the switch locks out positively at a given value of current it will close positively when the current has dropped ten per cent below that value. This means that the maximum and minimum accelerating current values can, with the requisite number of switches, be kept within five per cent above and five per cent below a horizontal line which represents a predetermined accelerating current of constant value.

In any calculations which are made as to the theoretically proper number of switches it must be borne in mind that the self-induction of the motor windings enters as an important factor, the peaks of current occurring at the instant of cutting out a given amount of resistance being in no case as great as a consideration of ohmic resistance alone would indicate.

FIG. 14

Figs. 12 and 13 show respectively a front view and a diagram of connections of a special controller for governing motors driving certain kinds of machine tools such as boring mills and pipe threading machines. In addition to securing automatic current limit acceleration in the manner previously described, this controller provides for bringing the motor to rest promptly by means of dynamic braking, the braking current being also kept within safe limits by the current limit feature of the switches which govern the acceleration.

This starter is provided with a main switch having a shunt-wound actuating coil and a dynamic-braking switch constructed in like manner. The operator's control is through push-buttoms marked " start " and " stop " respectively. When the " start " button is pushed the circuit of the actuating winding of the main switch is closed, causing this switch to close, and the starting resistance is then cut out automatically by the series wound accelerating switches in the manner previously described.

When it is desired to stop the "stop" button is pushed. This opens the circuit of the actuating winding of the main switch and closes the circuit of the winding of the dynamic braking switch, which then closes, establishing a local circuit across the armature, this circuit including the starting resistance and the actuating winding of the first resistance switch. As the motor slows down the dynamic braking current decreases and the first switch closes, thus cutting out a portion of the resistance in the dynamic braking circuit and at the same time closing the circuit through the winding of the second resistance controlling switch, which in turn closes and cuts out a second section of resistance when the current has dropped to the value for which the switch is adjusted. Both the starting current and the dynamic braking current are therefore under automatic current limit control and are maintained within safe limits.

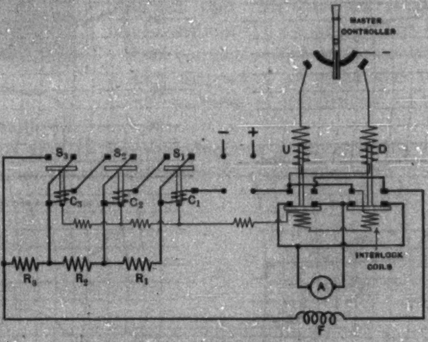


Fig. 15—Wiring Diagram

Fig. 14 is a front view of a 75-h.p. reversing controller specifically designed for steel mill service, and Fig. 15 shows the connections of this controller.

Reversal of the motor is provided for by two double pole magnetic switches having shunt wound actuating coils. The switches are mechanically interlocked in such a way that when one is closed the closure of the other is prohibited.

The actuating windings of the reversing switches are under the control of a suitable master controller in the hands of the operator. The motor circuit is initially closed at the contacts of one or the other reverser switches, this initial current flowing also through the winding of the first series wound switch. When the motor current has dropped to the predetermined accelerating value the first accelerating switch closes, short-circuiting the first section of resistance and establishing a circuit through the actuating winding of the second accelerating switch. The automatic cutting out of resistance continues in a similar manner till the motor is connected across the line.

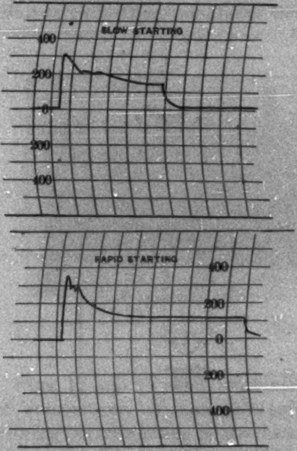


FIG. 16

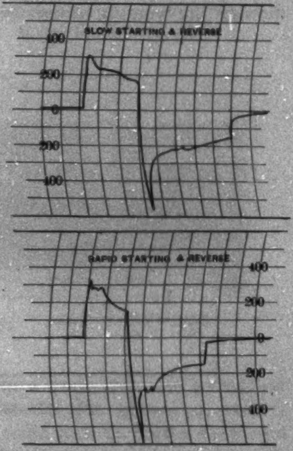


FIG. 17

The wiring diagram Fig. 15 shows a modified connection of the actuating windings of the accelerating switches, these windings being so arranged that they remain in series with the motor while the motor is running. A separate holding coil is therefore not required on the last switch.

As previously pointed out, the orderly or successive closure of the accelerating switches is provided for without the use of auxiliary or interlock contacts.

In a controller which is rapidly reversed it is essential to provide that all of the starting resistance be in circuit when the motor connections are reversed. This is provided for by two "lock-out" magnets placed immediately below the movable members of the reversing switches in such a way as to lock them out, thus preventing closure of the switches when the magnets are energized. The windings of these magnets are so connected that they are energized whenever any of the accelerating switches is closed. The reverser therefore cannot be operated until all three of the accelerating switches have opened, thus inserting all of the resistance in the motor circuit. It will be observed that this interlock is also obtained without the use of auxiliary or interlock contacts. The entire controller is in fact stripped of all small and delicate parts, in view of conditions to be met in steel mill service.

FIG. 18

Figs. 16 and 17 are reproductions of accelerating current curves taken on this controller in connection with a 75-h.p. 220-volt series wound motor. Fig. 16 shows the accelerating curves in simple starting, under different adjustments of the switches to secure slow and rapid starting.

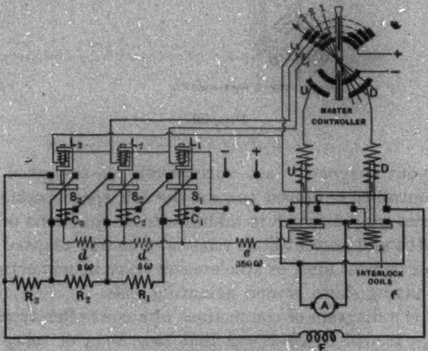


FIG. 19—Wiring Diagram

Fig. 17 shows current curves taken under similar conditions, the motor being reversed. Since there is no arcing at the contacts of the accelerating switches they may be readily enclosed in such a way that their adjustment cannot be tampered with.

The controller illustrated in Figs. 14 and 15 does not provide for speed control. Where it is necessary that the operator have control of the speed of the motor, this is provided for by "holding-out magnets" which prevent actuation of the accelerating switches when the "holding-out magnets" are energized.

Fig. 18 illustrates a unit switch equipped with a "holding-out magnet", and Fig. 19 is a diagram of connections of a controller arranged for speed control. It will be seen that the "holding-out magnets" are successively de-energized as the master controller is moved toward the full speed position.

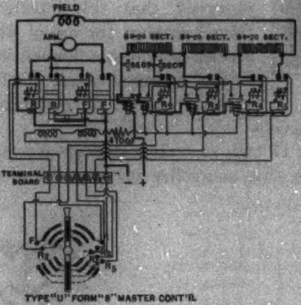


FIG. 20

The series wound switch in addition to its functions of a combined switch and current limit relay is of course adapted for use as a simple current limit or acceleration relay in connection with switches having shunt wound actuating coils.

Fig. 20 is a diagram of connections of a controller arranged in this way. It will be observed that this form of relay stands normally in the open or safe position and successive switches cannot close till the corresponding relays have closed their contacts. This arrangement provides a further safety feature in that it protects the motor from danger due to open circuits in the resistance and connections. The closure of successive resistance controlling switches depends not merely upon the closure of a preceding switch, but upon the closure of the main circuit controlled by a preceding switch. In case there is an open connection in the resistance controlled by one of the switches, the accelerating relay controlling the succeeding switch is not energized and the cutting out of resistance must stop at that point till the break is repaired.

DISCUSSION ON "AUTOMATIC MOTOR CONTROL FOR DIRECT-CURRENT MOTORS." CHICAGO, JUNE 28, 1911.

E. J. Murphy: I have listened with pleasure to Mr. Eastwood's able presentation, and can truly say that it represents a very great step towards the ideal which designers of control apparatus have been striving to attain, namely, an automatic motor control in which complicated wiring and numerous interlocks and relays have to a great extent been eliminated. It has been my privilege to work along those lines in which a contactor actuated by a series coil also contains the characteristic of a current limit relay. The illustrations shown and described herewith represent a type of contactor which was developed to meet steel mill operating conditions; in so doing it was decided to embody the best features of the shunt wound contactors which have proven so satisfactory after many years of the most exacting service; the most important feature being the reduction of the number of contact surfaces to a minimum, the use of a solid and easily replaceable rolling contact with vertical contact faces insuring against trouble due to the accumulation of dust or dirt upon them. The above consideration led to the adoption of a pivoted armature member which possessed the further advantage of operating with a minimum of friction, which is highly advantageous in obtaining a close and uniform adjustment. This arrangement of contacts also makes possible, when equipped with blow-out coils, the disrupting of heavy currents which is advantageous in certain applications of motor control. I wish to say, however, that this series contactor when used in an ordinary starting or reversing equipment is not called upon to open any appreciable current, making magnetic blow-out coils unnecessary. Your attention is particularly drawn to a very simple and effective method of connection, which makes it imperative that the contactors close in proper sequence, only one contactor being closed at a time. It should also be noted when the last contactor goes in, the other accelerating contactors are open while the motor is running. The above condition is brought about by means of the series coils only, no extra fine wire windings being necessary. This arrangement operates perfectly on a quick reversing equipment without any additional interlocking coils for delaying the action of the reversing line contactor.

Fig. 1 shows the contactor with the switch in the open position. C is a series wound actuating coil with a vertical iron core which projects through the brass supporting block B, and forms a pole face adapted to attract the cast iron armature A, across the upper air gap G_1. This armature is pivoted at P and carries the moving contact T, also the vertical iron strip L. The lower end of L forms a pole face which is attracted across the lower air gap G_2 by the horizontal iron extension E at the bottom of coil C. The armature A and the strip L form a bell crank lever: the attraction at the upper gap G_1 tends to close the switch and the attraction at the lower gap G_2 tends to hold the switch in the open position. The brass nut *N*, provided with locking spring, forms a stop for the strip *L*, thus regulating the length of the lower air gap G_2. This adjustment determines the current value at which the switch will close. (A more satisfactory adjusting device is shown in Fig. 2.) A vertical iron strip *S* of limited cross section connects the horizontal projection *E* and the iron casting to which the moving element is pivoted at *P*. This strip *S* forms a magnetic shunt to the lower air gap G_2, thus providing an alternative path for the magnetic flux.

The path of the magnetic flux is as follows: starting from the upper end of the core in coil *C*, across the gap G_1, along the armature *A*, to the pivot *P* where the flux divides, one portion flowing down the strip *L*, across the gap to the projection *E*. Another portion flows down the iron shunt *S* to the projection *E*. The total flux then flows along *E* to the magnet core of coil.

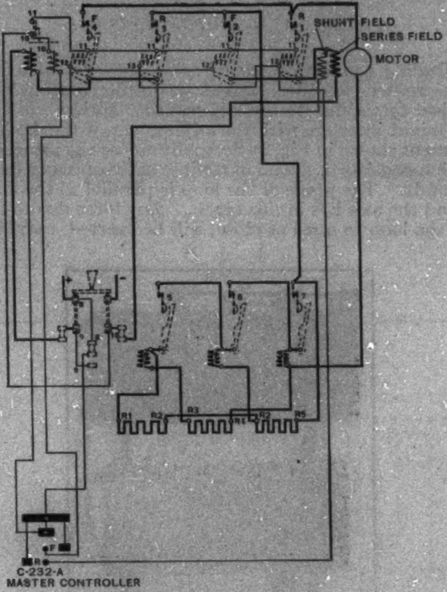
T
A
P
G1
L
S
C
D
G2
N
E

FIG. 1

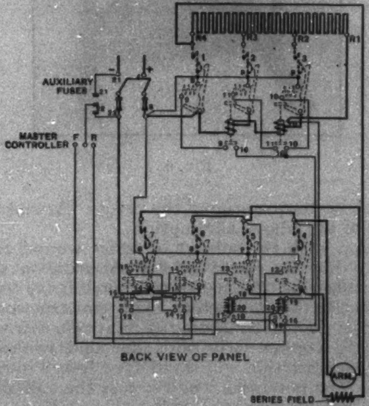
When current is switched through the coil *C* and this current is higher than the closing value for which the device is adjusted, the attraction across the lower gap G_2 is sufficient to hold the switch open against the attraction across the upper gap G_1. When the current falls, due to the acceleration of the motor, the magnetic flux in all parts of the magnetic circuit will decrease. The permeability of the iron shunt *S* will therefore increase, and in consequence, will carry a larger proportion of the flux relative to the lower gap G_2; these parts of the magnetic circuit being in parallel. The attraction across the lower gap G_2 will fall at a greater rate than the decrease in the attraction at the upper gap G_1, and finally, when the current arrives at the adjusted closing value, the attraction at the lower gap G_2 can no longer hold the moving element and the switch will close.

There was one serious difficulty which had to be overcome in the design, *i.e.*, to make certain that the contactor would hold open when the first rush of current through a highly inductive circuit was very little above the value at which the device was set to trip. This problem was solved by encircling the iron shunt S with a low resistance copper band D. The rapid rise in the flux value in the shunt S when the current is first switched on, generates a momentary heavy current in the copper band which opposes the increase of the flux. This action causes a larger proportion of flux to be forced across the gap G_2 while the current is rising, thereby increasing the attraction at the point until the current has risen to a safe value. In quick reversing equipments, the adoption of a longer copper band as shown in Fig. 2, rendered unnecessary the use of complicated interlocking devices.

FIG. 2


SHUNT FIELD
SERIES FIELD
MOTOR
F
R
R1
R2
R3
R4
R2
R5
C-232-A
MASTER CONTROLLER

MECHANICAL INTERLOCK
BETWEEN CONTACTORS LAND 2, 3 AND 4
BACK VIEW OF PANEL


R4
R3
R2
R1
AUXILIARY
FUSES
MASTER
CONTROLLER
F
R
BACK VIEW OF PANEL
ARM.
SERIES FIELD

MECHANICAL INTERLOCKS BETWEEN 4 AND 5, 6 AND 7

FIG. 3

The flexible connection for carrying the current around the pivot presented another serious problem, inasmuch as the mechanical forces due to the stiffness or " spring " of such connection might interfere with the adjustment of the device. The arrangement shown in Fig. 2 effectually solves the problem. The connection consists of a loop of flexible cable of many fine copper wire strands. The plane of the loop is parallel to the axis of the pivot, and the axis lies in this plane. Any force due to the tendency of the loop to open or close, will be exerted, radially across the pivot, with no torque around the pivot. Actual tests proved the accuracy of the above assumption.

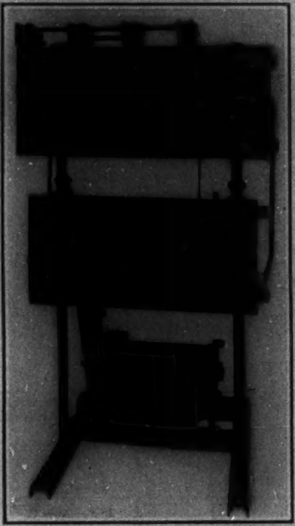


FIG. 4

In connection with the subject of series wound contactors in general, I note that Mr. Eastwood did not bring out one very important advantage, *i.e.*, the use of coil windings of few turns and large cross section of conductor. The construction shown in Fig. 2 is typical; the coil consisting of relatively few turns of bare edgewise wound copper strip with one end connected to the frame. This construction will stand very heavy overloads without damage. The potential strain across the coil and from coil to spool is only a fraction of a volt.

Fig. 2 also shows an improved adjustment for the lower gap G_2. The lower end of the vertical strip L abuts against the head of a fixed brass stud which supports an iron thimble. This thimble can be screwed along the stud, thereby controlling the width of the air gap G_2. Simple and positive locking devices are provided.

Fig. 3 shows the contrast between two connection diagrams for starting and reversing a direct current motor. The lower diagram shows the old fashioned arrangement with current limit relays operating shunt wound contactors with numerous electrical interlocks. The upper diagram shows the series contactor accelerating arrangement for the same duty, no electrical interlocks being required.

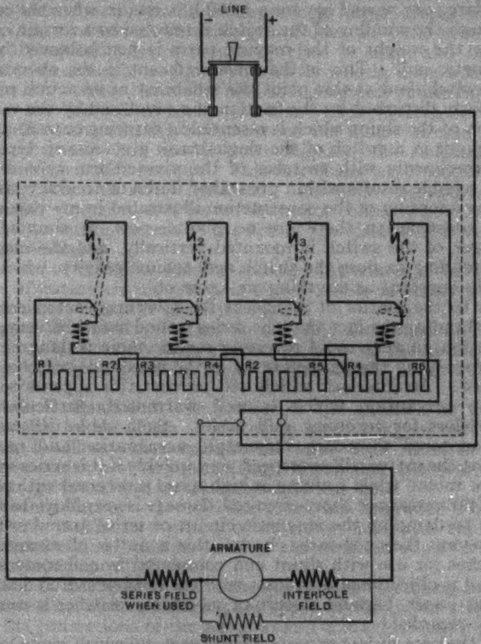

LINE
-
+
1
2
3
4
R1
R2
R3
R4
R2
R5
R4
R6
ARMATURE
SERIES FIELD WHEN USED
INTERPOLE FIELD
SHUNT FIELD

FIG. 5

Fig. 4 shows the front view of a starting and reversing panel using series accelerating contactors designed for heavy steel mill duty and Fig. 5 shows a wiring diagram of a very simple motor starting panel, using four series wound accelerating contactors with hand operated line switch and fuses.

Arthur C. Eastwood: As to the matter of contacts, brought up by Mr. Murphy, it must be remembered that this switch acts not only as a switch, but also as a relay. Whether the switch is a small one wound say for a one-horse-power motor, or a large one wound say for a 1,000-h.p. motor, when the current through the winding of the switch is reduced to a certain critical value the weight of the moving parts is just balanced by the magnetic pull. This is the sensitive point in the operation of the switch, and at this point the reliability of its action may be seriously disturbed by the friction of a pivot and by the variable action of the shunt which is essential in carrying current around the pivot in a switch of the single-break pivoted-arm type.

Experiments with switches of the pivoted-arm type did not give reliable results within prescribed limits of accuracy, and led to the adoption of the construction illustrated in my paper. In this construction there are no pivots, pins, or shunts. The plunger of the switch is mounted vertically, and the magnetic pull tending to close the switch acts against gravity, which is as nearly constant as anything we know of.

As to the matter of interlocks for reversing controllers, notwithstanding the fact that the series wound switch is very quick in action, in very rapid reversing service there is danger of the reverser being thrown before all of the resistance switches have opened. An interlock which will prevent this appears to be a safety precaution which is well warranted, particularly in controllers for reversing mill tables. Such tables are usually over-motored to secure very rapid acceleration and reversal, so that the motor will overspeed very quickly if it is series wound. If the motor while running at high speed is reversed with part or all of the resistance short-circuited, damage is very likely to result.

As to damping the magnetic circuit of series wound switches to prevent their too-early closure, this is not at all necessary in switches for use with shunt and compound wound motors. In fact, it is objectionable at least with the form of switch described in this paper, because closure of successive switches is unnecessarily retarded.

In the case of larger series wound motors, which give a circuit of high self-induction, causing the motor current to build up gradually, there is a tendency for the switches to close before the current has reached the lock-out value for which the switches are adjusted. However, the series wound switch is no more subject to this action than the ordinary "throttles" or accelerating relays which have been used in the past.

Even in the case of large series wound motors it has been found that if the resistance may be so proportioned that peaks of current equivalent to 150 per cent of the current at which the switch is adjusted to close, occur at the closure of each successive resistance switch, reliable locking-out of the switches occurs without resort to any specific means for retarding the action of the switches.

As to the matter of holding in the switches, this paper illustrates in Fig. 5 the use of a shunt holding coil on the last resistance switch, and in Fig. 15 the use of series coils throughout.

Admittedly the series coil is simpler in its connections and is more sturdy in construction, but its use has decided limitations. It has been found that in a surprisingly large proportion of motors, particularly those driving machine tools, the armature current frequently approaches very close to zero, and in the case of tools or machines equipped with fly-wheels, upon a sudden drop in line voltage the motor acts as a generator returning current to the line. This causes the last switch to drop out and insert all of the starting resistance in the motor circuit, and, when the motor has slowed down slightly, the resistance is again automatically cut out. This introduces an objectionable pumping action in many instances. The shunt holding-coil is free of this objection, as it leaves the motor connected to the line and free to return current to the line at the instant of a sudden drop in voltage.

The use of the series holding coil also introduces a resistance in the armature circuit which is objectionable in shunt wound motors where constant speed is required.

Ragner Wikander: I want to ask Mr. Eastwood and Mr. Murphy whether they have made any tests of the application of this principle, possibly somewhat modified, to alternating current?

Arthur C. Eastwood: In answer to the question as to the adaptability of this form of switch to alternating current controllers, I will say that experiments have been made in that direction which are very promising. I am not, however, prepared to go into detail on the subject at this time.

Theodore Varney: I would like to ask Mr. Eastwood if he has found any satisfactory means of notching back with the controller he described, that is, opening the switches one at a time, without opening all of them.

Arthur C. Eastwood: As to the question of "notching back" the controller, that is, reducing the speed of the motor step-by-step, the connections of the series wound contactors lose a great deal of their beautiful simplicity when this must be done.

There is no particular complication in a controller for "notching up" the speed of the motor step-by-step. Such a controller is shown in Fig. 19 of the paper.

When it is desirable to reduce as well as to increase the speed of the motor in a step-by-step manner under the control of the operator, a controller such as that shown in Fig. 20 may be used. In this controller the resistance switches are actuated by shunt wound magnets, and are governed as to the time of their closure by individual series relays.

A paper presented at the 28th Annual Convention of the American Institute of Electrical Engineers, Chicago, Ill., June 28, 1911.

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SOME LIMITATIONS OF RHEOSTATIC CONTROL

BY G. R. RADLEY AND L. L. TATUM

We may consider the limits of rheostatic control under three classes, *functional*, where the limitations are inherent to the type of control; *resistance material*, where the limitations are due to physical characteristics of the rheostat material, and *switching devices*, where the limitations apply to the method of adjusting resistance.

Functional Limitations

Under this heading, there are two general classes, those in which the load is predetermined, and absolutely under the control of the operator such as a field rheostat, and those in which the load is dependent on a variable factor, not absolutely of a predetermined value, such as a motor speed regulator with varying load on the motor.

In the first type, the field between actual physical limits is wide, but commercial limitations are worthy of consideration. Inherently all such devices are heat dissipators and the most important commercial limitation is the compromise of three variables; watts to be dissipated, allowable temperature rise, and physical dimensions. The discussion of these limitations which are common to all forms of rheostatic devices will be taken up later under the subject of "Limitations of Resistance Material."

Fineness of regulation is commercially limited. A field rheostat must be able to adjust the voltage of the generator by reasonably fine increments throughout the working range both of load and of speed of prime mover. If the range is wide, and the regulation desired is fine, the number of steps to obtain this range increases and while no physical limitations appear, the cost is increased. A fineness of regulation closer than ½ of one per cent of the rated voltage is ordinarily unnecessary, and generally this fineness may be obtained with a variation in excitation current of 1.5 per cent per step. For most machines 60 steps, thus representing in the neighborhood of 25 or 30 per cent of line voltage variation is ample. If, however, the major portion of this 25 per cent variation is outside the normal working range, then this number of steps may be insufficient. This condition may be overcome by the introduction of coarse steps in that portion of the range which is not normally used. For voltages above the working range, a single fixed step of resistance may serve to throw the normal voltage into the center of the adjusting range. Similarly below operating voltages a few coarse steps may be wanted for lowering the voltage to a satisfactory point for cutting out a generator.

Fineness of stepping over a wide range affects the size by increasing the watt dissipating material, as well as by increasing the number of switching points. Coarse steps tend to cheapen the rheostat but there are limits in this direction which will be discussed under contact limitations.

When a generator is capable of voltages much above normal, a fixed step of resistance results in economy of wattage capacity in the rheostat without approaching the contact limits, protects the machine from excessive heating of fields, and prevents excessive voltage on the line.

For use with automatic voltage regulators which require a wide range of generator excitation, coarse steps over most of the range with fine steps around normal, for possible hand regulation, reduces the size of the rheostat materially.

Another class of rheostatic device very similar in its functions to the field rheostat is the lamp dimmer. Here the conditions are even better defined than for the rheostat, as the dimmer is connected across a constant voltage supply in series with a quite definitely known resistance. The same general limitations apply, however: the coarser the stepping the smaller and cheaper is the rheostat.

Typical of the second class, namely, the type of control where there exists in the circuit a variable element which may be independent of the adjustment of the rheostat, are motor starters, or speed regulators where the counter voltage of the motor may be dependent on the load as well as on the adjustable resistance. Arc lamp resistances are more or less similar in their behavior. For this type of apparatus the governing feature is "load". Ohm's law must ever be in mind in considering such devices.

For a fixed value of R, E will vary directly as the current in the resistance, and when used as a speed regulating device across a constant potential line, the difference between the voltage drop in the resistance and the line voltage must be the counter e.m.f. of the motor. If the load on the motor varies, as when driving a machine tool such as lathe or planer, the voltage drop across the resistance must vary in direct proportion and the motor speed will vary inversely as the load. The inherently bad effect of such instability of speed regulation on machine tool work is too well understood to need discussion.

Where the load of the motor at any speed is approximately constant as when driving fans, pumps, printing presses, long line shafts, etc., resistance control is practical, although not always economical. Where the required torque decreases with the speed, as in the case of fans or centrifugal pumps the use of resistance is economical, since it reduces the current taken from the line, but where the torque is constant as for plunger pumps or positive pressure blowers, the only economy obtained by such control is in reduction of wear and tear on the apparatus, although convenience may warrant its installation independent of economical considerations.

On motor starters or regulators, the limit of coarseness of stepping is the increase in voltage the motor will stand without objectionable surge of current. This is a function of the motor and line resistance. A low motor resistance means a large current with small voltage rise at its terminals. A small high resistance series motor may not take an objectionable surge even if given full line voltage, while a large shunt-wound machine may not stand more than a few per cent voltage increase without excessive currents. This limit cannot be predetermined accurately as the inductance of the circuit, reaction of armature current surge on field strength, and momentary acceleration all tend to damp out the high peaks and give less than the calculated current surge for a given voltage increase.

This limit of stepping of resistance is most pronounced with the motor near normal speed or with little resistance in circuit. Theoretically for a 50 per cent overload surge we should be able to reduce the ohms in circuit to $\frac{2}{3}$ the previous value whenever the current has fallen to normal. This means that the ohmic value of the steps decreases toward the short circuit end.

This limits the arrangement of the steps on speed regulators since a regulator must also perform the functions of a starter.

If equal percentage increase in speed per step is wanted, (a geometrical progression) the last steps must be larger than the first, but this is the reverse of what is possible with equal surges. If equal speed increments are wanted, (an arithmetical progression) the steps should be of equal ohms, approaching more nearly to the starting requirements, but a compromise between the desirable speed curve and good starting characteristics must generally be made.

While the coarseness of steps is thus limited, there is no functional limit to the fineness of them, commercial considerations alone governing this.

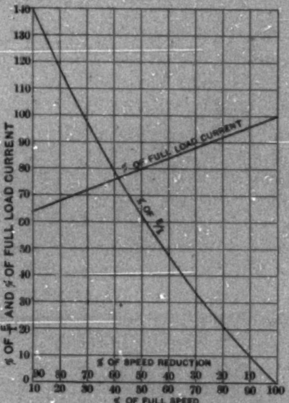

Fig. 1—Relation between speed, current and resistance assumed for machine regulation design.

Two distinct types of armature speed regulating devices are commercially recognized. These are commonly known as "machine type" and "fan type". Machine type is suitable for motors where the torque or current necessary for operation of the motor is approximately constant.

Fan type is the term applied to devices where the torque falls off as the speed decreases. As it is often impractical to determine the actual load a motor is to drive, one manufacturer designs a machine type regulator for 50 per cent reduction in speed with 80 per cent of the rated motor current thus allowing for the desired speed regulation with a 20 per cent variation in the actual load. If the motor runs at its full rated current, the speed reduction possible with all resistance in circuit will then be 62½ per cent.

The relation of resistance necessary to give any desired decrease in speed on the assumption that the load current follows a straight line from full load at full speed to 80 per cent of load at half speed is given in Fig. 1. The resistance is expressed in per cent of line volts divided by rated current of motor, thus making the formula applicable for all voltages and motor ratings. Fig. 2 shows a similar curve as laid out for the typical fan load. Theoretically, the horse power of a fan varies as the cube of the speed. Its torque therefore varies as the square of the speed and the current in the armature circuit should vary as the square of the speed. The friction losses will, however, vary directly as the speed, so that the total current in the motor armature should vary along a line between a straight line and the square curve. The effect of the friction losses will be much greater with small fans and at low speed and Fig. 2 therefore gives several current curves for motors of different sizes, the large sizes approaching more closely to a square curve, while the small sizes more closely approach a straight line.

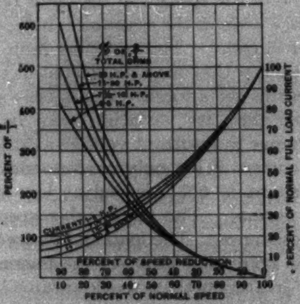

FIG. 2—Curves for fan regulation by armature resistance.

From an inspection of these curves the fact becomes apparent that the characteristics of the load, including its limiting variations, must be known if accurate speed control is expected from commercially standard apparatus.

There are some calls for more than 50 per cent speed reduction for special purposes. Ninety per cent by armature resistance may even be necessary. If 90 per cent of the line voltage is dropped in the resistance with a given current, it is evident that an increase of 11 per cent in current value will increase the resistance drop to full line voltage and leave nothing for counter voltage. If the current decreases 11 per cent the resistance drop falls to 80 per cent and the motor speeds up to double the desired speed. For such wide speed reductions by straight series resistance it is therefore necessary that the load be determined very accurately. These low speeds may be steadied by the use of a resistance in shunt to the armature. The effect of this is to make a portion of the current in the series resistance, and thus part of the voltage drop in the resistance, independent of the variations in motor current. The practical limit of this scheme is the amount of energy that may be wasted in the resistance. If the motor current in the armature is infinitely small compared to the line current, then its variation may be very wide with inappreciable change in resultant voltage at the motor terminals. A large wasted current is not only uneconomical but impractical. The armature shunt is only needed at low speeds, say below 25 per cent of normal. The next higher speed would be with straight series resistance. The load and desired speed determine the ohms at this point and thus set the maximum value of the total current. Greater currents would mean a bad jump in speed while lower currents give less steadying of the low speed. By the following formulas the values of shunting resistance may easily be determined for any given set of conditions.

Let E = line volts.

E_a = volts counter e.m.f. of armature.

R = ohms series resistance. This is dictated by desired speed with series resistance only.

R_a = ohms armature and brushes. May be neglected where $E_a > 20$ per cent E. For lower values of E_a, R_a may be taken: 10 per cent E/I for 5 h.p., 5 per cent E/I for 50 h.p., 3 per cent E/I for 200 h.p.

I_a = armature amperes—if not known may be estimated.

R_s = ohms in shunt. This will usually be the unknown. Derived from given values of I_a, derived values of R, known values of E and R_a, and desired values of E_a.
I_s = current through armature shunt, R_s.
I_r = current through series resistance R.
E_s = voltage across armature shunt, R_s.

Then

$$I_r = \frac{E - E_a - I_a\, R_a}{R}, \quad I_s = I_r - I_a, \quad E_s = E_a + I_a\, R_a$$

and

$$R_s = \frac{E_s}{I_s}, \quad \text{or } R_s = \frac{R.E_a + R.I_a\, R_a}{E - E_a - I_a\, R_a - R.I_a}$$

NOTE:—For constant field strength the speed in per cent of normal will vary as the counter e.m.f. of the armature in per cent of the counter e.m.f. at normal speed. This counter e.m.f. or E_a at normal speed equals $E - I_a\, R_a$ or line volts less resistance drop in the armature. $I_a\, R_a$ for speeds above 20 per cent and for large motors may be ignored.

RESISTANCE MATERIAL

The limiting features in the resistance material, or resistor, appear in getting the current into the resistor and getting the heat out of it. The limits for various materials used as resistors are sometimes found from one factor and sometimes from the other. Consider in a general way the matter of getting current into a resistor. Since the resistor is specifically designed for the dissipation of heat, we should expect it to reach a fairly high temperature. While the resistor itself may be of a material which will stand high temperature without oxidation or deterioration of its surface, the material commonly used for connectors, or conductors to such resistors, is subject to deterioration at reasonably low temperatures. It is necessary therefore, that the terminals of the resistors be specially designed to hold down the temperatures at this point. A terminal attached to a hot resistor must necessarily heat considerably by conduction, and if to this conduction is added a considerable amount of internally generated heat, the temperature is apt to be abnormally high. A gradation of temperature is wanted between the lead wires and the resistor itself, and the temperature of the lead wire and terminal should be kept low enough to prevent the melting of solder. One of the best examples of trouble with terminals is in the use of carbon resistances. Here the resistance of the contact is generally higher per unit of area than that of the resistor. Since the current is necessarily the same in resistor and terminal, this local increase in R means local heating and the use of carbon or graphite disk resistance which has many most excellent qualities has been limited by this terminal trouble. The same is true of water resistances. The highest resistance is ordinarily at the electrodes causing local heating.

How to get the heat out of the resistance is determined by a study of the laws of the flow of heat. The heat can be dissipated by radiation, by conduction, or by convection currents of fluids. All three methods are usually available to a greater or less extent. In the case of enclosed resistances it is almost entirely conduction from the wire to the exterior surface. In the majority of cases, the final disposition of the heat is into the air, the greater portion of this being by convection currents at ordinary temperatures, although at high temperatures, radiation plays a very important part.

Since practically all of the heat from a rheostat must be carried away by the air the actual design for a given limiting temperature both of issuing air and of rheostat exterior must be based on the laws of ventilation. The highest efficiency occurs when for a given amount of resistance material the quantity of air passed through the rheostat becomes a maximum. Vertical flues are more effective than horizontal baffles. The higher the temperature of the flue the more rapid the convective air currents and the greater the permissible watts for a given top area. What shall we take as a limit? Pieces of paper, wood, cloth, etc., begin to char at about 225 deg. cent., or 200 deg. rise above the usual room temperature. A 150 deg. cent. rise would then seem to be a safe point to choose for a limiting temperature. But this limit need only apply to the parts of the rheostat which may come in contact with external objects. With embedded rheostats this would mean the case. In the open type, the resistor itself would be measured. But where the resistor is provided with a frame and has screens to prevent the entrance of foreign combustible material into the enclosure, the temperature limit of 150 deg. rise should apply only to the *top* or hottest part of this frame. The interior heating surfaces or flues should be permitted say double this, or 300 deg. cent. rise. There would then still be a considerable factor for unforeseen overload before reaching a red heat, which occurs at from 500 to 600 deg. cent.

With these maximum limits established it then only remains to consider the resistor materials and the temperatures they may stand without deterioration. For alloys such as German silver this is the point at which the zinc distills off, changing its characteristics as a resistor. For alloys containing manganese, the distilling point of this metal is the limit. For wrought iron or iron wire, the limit is the temperature at which the resistor becomes plastic, which is close to that at which oxidation becomes bad. Cast iron can be run indefinitely at a dull red heat, with only very slow oxidation, but at white heat the oxidation is much more rapid, and the melting point is the final limit. For carbon or graphite, a bright red heat allows slow oxidation but without immediate deterioration.

While these are ultimate temperature limits, a factor of safety is desired and the limiting of the air temperature tends to hold temperature of resistor much lower. As a rough average of commercial structures with natural ventilation, the surface temperature of an open resistor, such as a cast iron grid, will be about 350 deg. cent with the air issuing from top of frame at 175 deg. cent. The temperature of an imbedded resistor may be much higher than the surface of the enclosing material, and this temperature gradient from resistor to surface will vary greatly with the kind of material.

Probably the best way to bring out some of the limits of resistance material will be to consider specific forms. For very large currents used only for emergency, or tests, a water rheostat is admirably adapted. The boiling point of the water is the temperature limit, but terminal troubles are the main factor. It is comparatively easy to get the current into the electrodes, but the high resistance between the electrodes and liquid conductors limits the current which can be carried per square inch of electrodes. This varies with the liquid, and also to some extent with the nature of the electrodes, so that no specific figures can be given here.

For large currents one naturally turns to iron for a cheap and sturdy resistor. Old rails have been used in some specific instances, but here the trouble is mainly one of getting the current into the resistor itself. A 30-ft. 60-lb. rail has a resistance of 0.001 ohm approximately. When used for very intermittent service, such as starting a large motor, it will absorb 220 kw. for one minute with a temperature rise of approximately 100 deg. cent. To get 220 kw. into the rail with a resistance of 0.001

ohm, means the use of 15,000 amperes, and the shape of a 60-lb. rail does not readily lend itself to the attachment of 15,000 ampere terminals. For regulating duty its shape makes it inefficient.

The limit of temperature of wrought iron or steel resistors is the plastic stage. To prevent deformation under their own weight would require frequent insulating supports, making such structures expensive and generally reducing ventilation.

Cast iron as a resistance material is cheap, easily formed so as to give good arrangements for terminal attachments, easily adjusted in section to the desired resistance, and has an extremely narrow temperature range during which it is plastic. Ordinarily if the plastic temperature is reached, it will very quickly pass to the melting point and the grid instead of remaining in circuit badly damaged, will melt and open the circuit.

Cast grids reach the limit of heavy currents due to terminal features, while with low currents the limit is the ability to get sufficiently high resistance. By casting the grid with considerable mass of metal at the point of terminal connection, the generation of heat in the terminal due to its own resistance is reduced. The conducted heat from the hot section is dissipated from the large terminal surface at a low temperature. The terminals may also be placed out of the heated air flue and in a column of comparatively cool air. Manufacturing conditions limit the size of these terminal lugs, and since the current is carried from one grid to the other through the surfaces of these lugs, this current capacity between lugs becomes a limiting feature. In ordinary commercial practice this limiting feature coincides fairly well with the limits of current capacity of wires which are easily handled for attachment into such terminals. About 300,000 cir. mil stranded wire is as heavy as should be used. When carrying current continuously this means about 400 amperes, while when worked very intermittently, it may be used up to 1200 or 1500 amperes. This is the top limit that should be used on a single circuit, and greater currents should be divided on parallel circuits.

The resistance that can be obtained determines the low current limit of cast iron grids. A section 3/32 by ⅛ in. by 8 in. long can be cast, but a long section, or several loops of this size will scarcely support its own weight, and must be supported. Cast iron varies a little in its specific resistance, castings from the same heat running about 500 ohms per cir. mil-ft. for heavy sections and a little higher, or about 550 ohms, for very thin sections. The thinnest practical section grid is commercially economical for continuous current dissipation down to about 20 amperes, but below that weight, space, and cost must be sacrificed.

Attempts have been made for years to find alloys of iron having a higher specific resistance, to extend the economical range of this construction below the 20-ampere limit. The high cost of these alloys has so far prevented their commercial adoption. Alloys of copper, nickel and other metals which have very high specific resistances are practically useless for this structure, because of their plastic stage being reached at comparatively low temperatures with the result that they distort under commercial operating conditions. The high cost of the alloy itself combined with the relatively low temperature at which it must be worked, makes other forms of supported material much more economical. While above 20 amperes continuous duty the cast grid has no serious rival, below 20 amperes some other form is necessary.

Space and weight consideration necessitate a resistor of high specific resistance. Iron wire meets this condition economically, but its high temperature coefficient and liability to rust, limit its field to fairly low temperatures. High resistance alloys are expensive and their commercial use requires that the weight be kept down to a minimum. More heat can be carried away from a wire by conduction through even poor heat conductors, than by convection of air and radiation, for a given temperature above the surrounding medium. This has led to covering such resistors with cement, enamel or mica, conducting the heat from the wire and distributing it over a larger surface from which it passes to the air with a lower surface temperature. Alloy resistance wires are generally plastic at comparatively low temperatures. This necessitates frequent points of support.

The limits of stiffness of resistor and its inherently small surface have led to a form consisting of a heat resisting insulating base, on which the wire is wound, and some heat resisting insulating covering attaching the wire to the base. The high current limit of such construction is primarily its cost, where cast iron grids can be economically used, coupled with difficulty of winding and clamping heavy resistor wires, and of bringing out suitable terminals. Unequal expansion of resistor and covering crack the latter if the wire is too heavy. There is no low current limit to such constructions. The resistance that can be put into a given space is limited only by the size and specific resistance of the wire obtainable.

The temperature limit of such resistance units is much the same as for cast grids. For the same temperature of air, 175 deg. cent. approximately the same temperature of unit surface may exist, about 350 deg. cent. The actual temperature of the resistor will vary widely with the thickness and nature of the covering over it. Alloys are obtainable which will be stable up to even 1500 deg. cent. while the covering will generally deteriorate at red heat or a little above.

For continuous duty the order of limitations for such units is, first, temperature of issuing air, second, temperature of covering and third, melting point of the resistor. When used for intermittent or starting duty the order of the limits may be reversed. It takes some time to heat up the resistor covering to a point where it will give up heat to the air. The entire heat generated during a period of service may be absorbed by the unit and only gradually conducted to the exterior.

With a heavy covering of low heat conductivity the maximum surface temperature may not be reached till several minutes after current is cut off. This indicates a steep temperature gradient in the covering. If the rate of heat generation in the resistor is higher than conduction can carry it away, the temperature of the resistor must rise. Up to a certain point this rise in temperature seems to increase the rate of heat conduction and a balance is reached if given sufficient time. There appears however, to be a limiting rate of watt dissipation for a given wire, above which the resistor melts or vaporizes almost as soon as current is put on, acting very much like an enclosed fuse. When this action has occurred it is easily detected by examination of such a damaged unit. If gradually overloaded the resistor opens at the weakest point, and shows evidence of high heat on the covering. If suddenly overloaded to this limit the temperature rises so rapidly that the weakest spot does not have time to interrupt the circuit before several other spots have melted and opened the circuit, apparently simultaneously, yet without any evidence of overheating showing on the covering.

For momentary, intermittent or starting duty, the order of limits is therefore first the temperature of the resistor, second that of the covering and third that of the air.

CONTACT LIMITS

The limitations of contacts or switching parts are carrying capacity, and commutating capacity, the latter including ability to make, as well as break a circuit.

The carrying capacity of a contact cannot be defined accurately by a current density per unit of area of contact, but involves the material of the surfaces, the pressure per unit of area, and the mass and surface adjacent to the contact.

Of the commercially possible materials silver is probably best. It has a fairly high specific heat and good heat conduction, and the oxide is a good conductor. The latter is the main point, as the insulating oxide of other metals tends to reduce the area of contact.

Copper, brass and carbon follow in the order given.

While carbon has a relatively high specific resistance and high contact resistance it is used very extensively as a material for sliding contacts because of its freedom from welding, and its ability to withstand local high temperature without injury.

Laminated copper leaf brushes giving a well distributed pressure over the contact area are commercially best for large currents.

Contacts or switching devices in connection with rheostats must generally commutate current as well as carry it, and this feature limits the use of the various forms.

A sliding contact can make a circuit only through a leading point or line. Where this circuit parallels another circuit of relatively high resistance nearly the entire current passes through the line contact. This tends to heat the contact locally. If there is a good mass of heat-absorbing material closely adjacent to the line, the actual temperature rise may be small, but if there is little mass the line may quickly reach the fusing point. With copper or brass this may result in welding; with carbon it will cause burning.

These considerations lead to the limits of capacity of forms of contact. Round buttons make contact with the shoe practically at a point, and the curved shape reduces the adjacent mass. Segment forms make contact on a line, with larger masses adjacent. Knife blade contacts make one, or with very good fitting, two line contacts with small mass. The " butt " type approaches surface contact, and if of massive form has the mass adjacent to all parts of the surface. A butt contact with a light spring is no better than a sliding contact.

On making a circuit the current tending to heat the point of contact is determined by the resistance in circuit and the voltage. For the same current the heating is the same no matter what the voltage. On opening a circuit the voltage is the controlling factor. Below about 27 volts, no arc will form, and the heating ceases when the surfaces separate. Above this an arc tends to form, with heating and burning. If the contacts are cold and massive, and the current small the arc may not heat enough metal even locally to maintain itself. Either high voltage or high current, or to consider both, a high energy loss, tends to neutralize the effect of mass by heating the arcing point faster than it is cooled by conduction.

This is illustrated by the arcing distance of inductive circuits. On a test of the length of arc maintained when one or more magnetic switch circuits were opened, using heavy copper contacts, separated at slow speed, it was found that up to a certain current for any given voltage the arc would not hold 0.01 in. The smallest current that would arc this distance would often arc across a gap five times as large. Raising the current value would often run the arcing length up faster than the current. These values would have been materially changed for contacts of different weight and shape.

There are five factors that limit the amount of resistance than can be cut into circuit; first, the voltage, determined approximately by the current times the resistance of the step. Since there is generally some induction in a circuit, tending to maintain the current at its initial value, the value of the current existing before the introduction of the resistance must be used. Second, the value of the current. Third, nature of the contact, Fourth, the length of the gap. Fifth, the speed of operation.

Below 27 volts the length of the gap need not be considered, but the other factors all enter by reason of local heating on reduced surface of contact.

Above 27 volts, unless the currents are small compared to mass of contacts, gap length is important and becomes a definite limiting feature on sliding contacts which must bridge the gap. Filling the gap with insulating material to prevent the moving contact from falling between the fixed contacts, is dangerous as the arc drawn over the surface carbonizes the insulator, even if contact dust does not form a leakage path over its surface.

Step voltages therefore limit the use of sliding contacts.

Knife blade contacts may be used when handled quickly to eliminate the effect of small surface and small mass. Butt contacts generally supply the mass element.

Applying these limits to types previously considered, we find that for field rheostats or dimmers, having relatively light contacts, small spacing, and slow or indefinite motions, stepping of resistance must be small to prevent arcing on cutting in resistance, and still smaller to prevent shunting too large a portion of the total current through a line contact when coming in or going off a contact.

On a motor speed regulator with sliding contacts and a device for holding the moving contact squarely on the fixed contact, coarser steps may be used as the local heating effect is eliminated. On a motor speed regulator having a switch form of contact the steps may be as coarse as the switch will open.

On a motor starter with sliding contacts the steps may be coarser than on a regulator as the service is intermittent and heating effect reduced. The resistance is not normally cut into circuit slowly, so the arcing effect of the voltage per step may be neglected. When stopping a motor by a resistance starter the current in the starter is low by reason of the motor counter voltage nearly equalling line voltage.

In conclusion it may be well to state a few factors which will serve as short cuts to the consideration of sizes of rheostats. The maximum energy dissipation in an adjustable resistance in series with a fixed resistance across a given voltage occurs when the adjustable resistance in circuit is equal in value to the fixed resistance.

When the voltage over the rheostat, varies as a result of changing its resistance, (as in a field regulator or dimmer) the series connection of steps makes the most efficient use of resistance material.

When the voltage over the rheostat, however, does not change greatly with a change in its resistance, parallel connection of steps gives the best use both of resistor and of contact material. A load rheostat, which is used in series with an external resistance of negligible value, is an example of this. Here each step is arranged to pass a certain current, and at maximum load all resistance material is active.